The Future of Nuclear Power

AN INTERDISCIPLINARY MIT STUDY

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Forward and Acknowledgments

We decided to study the future of nuclear power because we believe this technology, despite the challenges it faces, is an important option for the United States and the world to meet future energy needs without emitting carbon dioxide (CO_2) and other atmospheric pollutants. Other options include increased efficiency, renewables, and sequestration. We believe that all options should be preserved as nations develop strategies that provide energy while meeting important environmental challenges. The nuclear power option will only be exercised, however, if the technology demonstrates better economics, improved safety, successful waste management, and low proliferation risk, and if public policies place a significant value on electricity production that does not produce CO_2. Our study identifies the issues facing nuclear power and what might be done to overcome them.

Our audience is government, industry, and academic leaders with an interest in the management of the interrelated set of technical, economic, environmental, and political issues that must be addressed if large-scale deployment of new nuclear power generating facilities is to remain an option for providing a significant fraction of electricity supply in the middle of this century. We trust that our analysis and arguments will stimulate constructive dialogue about the way forward.

This study also reflects our conviction that the MIT community is well equipped to carry out interdisciplinary studies intended to shed light on complex socio-technical issues that will have a major impact on our economy and society. Nuclear power is but one example; we hope to encourage and participate in future studies with a similar purpose.

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Executive Summary

STUDY CONTEXT

Over the next 50 years, unless patterns change dramatically, energy production and use will contribute to global warming through large-scale greenhouse gas emissions — hundreds of billions of tonnes of carbon in the form of carbon dioxide. Nuclear power could be one option for reducing carbon emissions. At present, however, this is unlikely: nuclear power faces stagnation and decline.

This study analyzes what would be required to retain nuclear power as a significant option for reducing greenhouse gas emissions and meeting growing needs for electricity supply. Our analysis is guided by a global growth scenario that would expand current worldwide nuclear generating capacity almost threefold, to 1000 billion watts, by the year 2050. Such a deployment would avoid 1.8 billion tonnes of carbon emissions annually from coal plants, about 25% of the increment in carbon emissions otherwise expected in a business-as-usual scenario. This study also recommends changes in government policy and industrial practice needed in the relatively near term to retain an option for such an outcome.

We did not analyze other options for reducing carbon emissions — renewable energy sources, carbon sequestration, and increased energy efficiency — and therefore reach no conclusions about priorities among these efforts and nuclear power. In our judgment, it would be a mistake to exclude any of these four options at this time.

STUDY FINDINGS

For a large expansion of nuclear power to succeed, four critical problems must be overcome:

- Cost. In deregulated markets, nuclear power is not now cost competitive with coal and natural gas. However, plausible reductions by industry in capital cost, operation and maintenance costs, and construction time could reduce the gap. Carbon emission credits, if enacted by government, can give nuclear power a cost advantage.
- Safety. Modern reactor designs can achieve a very low risk of serious accidents, but “best practices” in construction and operation are essential. We know little about the safety of the overall fuel cycle, beyond reactor operation.
- Waste. Geological disposal is technically feasible but execution is yet to be demonstrated or certain. A convincing case has not been made that the long-term waste management benefits of advanced, closed fuel cycles involving reprocessing of spent fuel are outweighed by the short-term risks and costs. Improvement in the open, once through fuel cycle may offer waste management benefits as large as those claimed for the more expensive closed fuel cycles.
- Proliferation. The current international safeguards regime is inadequate to meet the security challenges of the expanded nuclear deployment contemplated in the global growth scenario. The reprocessing system now used in Europe, Japan, and Russia that involves separation and recycling of plutonium presents unwarranted proliferation risks.

We conclude that, over at least the next 50 years, the best choice to meet these challenges is the open, once-through fuel cycle. We judge that there are adequate uranium resources available at reasonable cost to support this choice under a global growth scenario.

Public acceptance will also be critical to expansion of nuclear power. Our survey results show that the public does not yet see nuclear power as a way to address global warming, suggesting that further public education may be necessary.

SELECTED RECOMMENDATIONS

- ☐ We support the Department of Energy (DOE) 2010 initiative to reduce costs through new design certification, site banking, and combined construction and operation licenses.
- ☐ The government should also share “first mover” costs for a limited number of power plants that represent safety-enhancing evolutionary reactor design. We propose a production tax credit for up to $200/kWe of the plant’s construction cost. This mechanism creates a strong incentive to complete and operate the plant and the mechanism is extendable to other carbon-free technologies. The government actions we recommend aim to challenge the industry to demonstrate the cost reductions claimed for new reactor construction, with industry assuming the risks and benefits beyond first- mover costs.
- ☐ Federal or state portfolio standards should include incremental nuclear power capacity as a carbon free source.
- ☐ The DOE should broaden its long-term waste R&D program, to include improved engineered barriers, investigation of alternative geological environments, and deep bore hole disposal. A system of central facilities to store spent fuel for many decades prior to geologic disposal should be an integral part of the waste management strategy. The U.S. should encourage greater harmonization of international standards and regulations for waste transportation, storage, and disposal.
- ☐ The International Atomic Energy Agency should have authority to inspect all suspect facilities (implement the Additional Protocol) and should develop a worldwide system for materials protection, control, and accountability that goes beyond accounting, reporting, and periodic inspections. The U.S. should monitor and influence developments in a broad range of enrichment technologies.
- ☐ The DOE R&D program should be realigned to focus on the open, once-through fuel cycle. It should also conduct an international uranium resource assessment; establish a large *nuclear system analysis, modeling, and simulation project*, including collection of engineering data, to assess alternative nuclear fuel cycle deployments relative to the four critical challenges; and halt development and demonstration of advanced fuel cycles or reactors until the results of the nuclear system analysis project are available.

CHAPTER 1 — THE FUTURE OF NUCLEAR POWER — OVERVIEW AND CONCLUSIONS

The generation of electricity from fossil fuels, notably natural gas and coal, is a major and growing contributor to the emission of carbon dioxide – a greenhouse gas that contributes significantly to global warming. We share the scientific consensus that these emissions must be reduced and believe that the U.S. will eventually join with other nations in the effort to do so.

At least for the next few decades, there are only a few realistic options for reducing carbon dioxide emissions from electricity generation:

- increase efficiency in electricity generation and use;
- expand use of renewable energy sources such as wind, solar, biomass, and geothermal;
- capture carbon dioxide emissions at fossil-fueled (especially coal) electric generating plants and permanently sequester the carbon; and
- increase use of nuclear power.

The goal of this interdisciplinary MIT study is not to predict which of these options will prevail or to argue for their comparative advantages. In *our view, it is likely that we shall need all of these options and accordingly it would be a mistake at this time to exclude any of these four options from an overall carbon emissions management strategy*. Rather we seek to explore and evaluate actions that could be taken to maintain nuclear power as one of the significant options for meeting future world energy needs at low cost and in an environmentally acceptable manner.

In our view, it would be a mistake at this time to exclude any of these four options from an overall carbon emissions management strategy.

In 2002, nuclear power supplied 20% of United States and 17% of world electricity consumption. Experts project worldwide electricity consumption will increase substantially in the coming decades, especially in the developing world, accompanying economic growth and social progress. However, official forecasts call for a mere 5% increase in nuclear electricity generating capacity worldwide by 2020 (and even this is questionable), while electricity use could grow by as much as 75%. These projections entail little new nuclear plant construction and reflect both economic considerations and growing anti-nuclear sentiment in key countries. The limited prospects for nuclear power today are attributable, ultimately, to four unresolved problems:

- *Costs: nuclear power has higher overall lifetime costs* compared to natural gas with combined cycle turbine technology (CCGT) and coal, at least in the absence of a carbon tax or an equivalent "cap and trade" mechanism for reducing carbon emissions;
- *Safety: nuclear power has perceived adverse safety, environmental, and health effects*, heightened by the 1979 Three Mile Island and 1986 Chernobyl reactor accidents, but also by accidents at fuel cycle facilities in the United States, Russia, and Japan. There is also growing concern about the safe and secure transportation of nuclear materials and the security of nuclear facilities from terrorist attack;
- *Proliferation: nuclear power entails potential security risks*, notably the possible misuse of commercial or associated nuclear facilities and operations to acquire technology or materials as a precursor to the acquisition of a nuclear weapons capability. Fuel cycles that involve the chemical reprocessing of spent fuel to separate weapons-usable plutonium and uranium enrichment technologies are of special concern, especially as nuclear power spreads around the world;
- *Waste: nuclear power has unresolved challenges in long-term management of radioactive wastes.* The United States and other countries have yet to implement final disposition of spent fuel or high level radioactive waste streams created at various stages of the nuclear fuel cycle. Since these radioactive wastes present some danger to present and future generations, the public and its elected representatives, as well as prospective investors in nuclear power plants, properly expect continuing and substantial progress towards solution to the waste disposal problem. Successful operation of the planned disposal facility at Yucca Mountain would ease, but not solve, the waste issue for the U.S. and other countries if nuclear power expands substantially.

We believe the nuclear option should be retained, precisely because it is an important carbon-free source of power.

Today, nuclear power is not an economically competitive choice. Moreover, unlike other energy technologies, nuclear power requires significant government involvement because of safety, proliferation, and waste concerns. If in the future carbon dioxide emissions carry a significant “price,” however, nuclear energy could be an important — indeed vital — option for generating electricity. We do not know whether this will occur. But *we believe the nuclear option should be retained, precisely because it is an important carbon-free source of power that can potentially make a significant contribution to future electricity supply*.

To preserve the nuclear option for the future requires overcoming the four challenges described above—costs, safety, proliferation, and wastes. These challenges will escalate if a significant number of new nuclear generating plants are built in a growing number of countries. The effort to overcome these challenges, however, is justified only if nuclear power can potentially contribute significantly to reducing global warming, which entails major expansion of nuclear power. In effect, preserving the nuclear option for the future means planning for growth, as well as for a future in which nuclear energy is a competitive, safer, and more secure source of power.

To explore these issues, our study postulates a *global growth scenario* that by mid-century would see 1000 to 1500 reactors of 1000 megawatt-electric (MWe) capacity each deployed worldwide, compared to a capacity equivalent to 366 such reactors now in service. Nuclear power expansion on this scale requires U.S. leadership, continued commitment by Japan, Korea, and Taiwan, a renewal of European activity, and wider deployment of nuclear power around the world. An illustrative deployment of 1000 reactors, each 1000 MWe in size, under this scenario is given in following table.

Global Growth Scenario

REGION	PROJECTED 2050 GWe CAPACITY	NUCLEAR ELECTRICITY MARKET SHARE	
		2000	2050
Total World	**1,000**	**17%**	**19%**
Developed world	625	23%	29%
U.S.	300		
Europe & Canada	210		
Developed East Asia	115		
FSU	50	16%	23%
Developing world	325	2%	11%
China, India, Pakistan	200		
Indonesia, Brazil, Mexico	75		
Other developing countries	50		

Projected capacity comes from the global electricity demand scenario in Appendix 2, which entails growth in global electricity consumption from 13.6 to 38.7 trillion kWhrs from 2000 to 2050 (2.1% annual growth). The market share in 2050 is predicated on 85% capacity factor for nuclear power reactors. Note that China, India, and Pakistan are nuclear weapons capable states. Other developing countries includes as leading contributors Iran, South Africa, Egypt, Thailand, Philippines, and Vietnam.

This scenario would displace a significant amount of carbon-emitting fossil fuel generation. In 2002, carbon equivalent emission from human activity was about 6,500 million tonnes per year; these emissions will probably more than double by 2050. The 1000 GWe of nuclear power postulated here would avoid annually about 800 million tonnes of carbon equivalent if the electricity generation displaced was gas-fired and 1,800 million tonnes if the generation was coal-fired, assuming no capture and sequestration of carbon dioxide from combustion sources.

FUEL CYCLE CHOICES

A critical factor for the future of an expanded nuclear power industry is the choice of the fuel cycle — what type of fuel is used, what types of reactors "burn" the fuel, and the method of disposal of the spent fuel. This choice affects all four key problems that confront nuclear power — costs, safety, proliferation risk, and waste disposal. For this study, we examined three representative nuclear fuel cycle deployments:

We believe that the world-wide supply of uranium ore is sufficient to fuel the deployment of 1,000 reactors over the next half century.

- ☐ *conventional thermal reactors operating in a "once-through" mode*, in which discharged spent fuel is sent directly to disposal;
- ☐ *thermal reactors with reprocessing in a "closed" fuel cycle*, which means that waste products are separated from unused fissionable material that is re-cycled as fuel into reactors. This includes the fuel cycle currently used in some countries in which plutonium is separated from spent fuel, fabricated into a mixed plutonium and uranium oxide fuel, and recycled to reactors for one pass[1];
- ☐ *fast reactors[2] with reprocessing in a balanced "closed" fuel cycle*, which means thermal reactors operated world-wide in "once-through" mode and a balanced number of fast reactors that destroy the actinides separated from thermal reactor spent fuel. The fast reactors, reprocessing, and fuel fabrication facilities would be co-located in secure nuclear energy "parks" in industrial countries.

Closed fuel cycles extend fuel supplies. The viability of the once-through alternative in a global growth scenario depends upon the amount of uranium resource that is available at economically attractive prices. *We believe that the world-wide supply of uranium ore is sufficient to fuel the deployment of 1000 reactors over the next half century* and to maintain this level of deployment over a 40 year lifetime of this fleet. This is an important foundation of our study, based upon currently available information and the history of natural resource supply.

The result of our detailed analysis of the relative merits of these representative fuel cycles with respect to key evaluation criteria can be summarized as follows: *The once through cycle has advantages in cost, proliferation, and fuel cycle safety*, and is disadvantageous only in respect to long-term waste disposal; the

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1. This fuel cycle is known as Plutonium Recycle Mixed Oxide, or PUREX/MOX.
2. A fast reactor more readily breeds fissionable isotopes-potential fuel-because it utilizes higher energy neutrons that in turn create more neutrons when absorbed by fertile elements, e.g. fissile Pu^{239} is bred from neutron absorption of U^{238} followed by beta (electron) emission from the nucleus.

two closed cycles have clear advantages only in long-term aspects of waste disposal, and disadvantages in cost, short-term waste issues, proliferation risk, and fuel cycle safety. (See Table.) Cost and waste criteria are likely to be the most crucial for determining nuclear power's future.

We have not found, and based on current knowledge do not believe it is realistic to expect, that there are new reactor and fuel cycle technologies that simultaneously overcome the problems of cost, safety, waste, and proliferation.

Fuel Cycle Types and Ratings

				SAFETY	
	ECONOMICS	**WASTE**	**PROLIFERATION**	**Reactor**	**Fuel Cycle**
Once through	+	× short term – long term	+	×	+
Closed thermal	–	– short term + long term	–	×	–
Closed fast	–	– short term + long term	–	**+ to –**	–

+ means relatively advantageous; × means relatively neutral; – means relatively disadvantageous

This table indicates broadly the relative advantage and disadvantage among the different type of nuclear fuel cycles. It does not indicate relative standing with respect to other electricity-generating technologies, where the criteria might be quite different (for example, the nonproliferation criterion applies only to nuclear).

Our analysis leads to a significant conclusion: *The once-through fuel cycle best meets the criteria of low costs and proliferation resistance*. Closed fuel cycles may have an advantage from the point of view of long-term waste disposal and, if it ever becomes relevant, resource extension. But closed fuel cycles will be more expensive than once-through cycles, until ore resources become very scarce. This is unlikely to happen, even with significant growth in nuclear power, until at least the second half of this century, and probably considerably later still. Thus our most important recommendation is:

For the next decades, government and industry in the U.S. and elsewhere should give priority to the deployment of the once-through fuel cycle, rather than the development of more expensive closed fuel cycle technology involving reprocessing and new advanced thermal or fast reactor technologies.

This recommendation implies a major re-ordering of priorities of the U.S. Department of Energy nuclear R&D programs.

PUBLIC ATTITUDES TOWARD NUCLEAR POWER

Expanded deployment of nuclear power requires public acceptance of this energy source. Our review of survey results shows that a majority of Americans and Europeans oppose building new nuclear power plants to meet future energy needs. To understand why, we surveyed 1350 adults in the US about their attitudes toward energy in general and nuclear power in particular. Three important and unexpected results emerged from that survey:

- The U.S. public's attitudes are informed almost entirely by their perceptions of the technology, rather than by politics or by demographics such as income, education, and gender.
- The U.S. public's views on nuclear waste, safety, and costs are critical to their judgments about the future deployment of this technology. Technological improvements that lower costs and improve safety and waste problems can increase public support substantially.
- In the United States, people do not connect concern about global warming with carbon-free nuclear power. There is no difference in support for building more nuclear power plants between those who are very concerned about global warming and those who are not. Public education may help improve understanding about the link between global warming, fossil fuel usage, and the need for low-carbon energy sources.

There are two implications of these findings for our study: first, the U.S. public is unlikely to support nuclear power expansion without substantial improvements in costs and technology. Second, the carbon-free character of nuclear power, the major motivation for our study, does not appear to motivate the U.S. general public to prefer expansion of the nuclear option.

The U.S. public is unlikely to support nuclear power expansion without substantial improvements in costs and technology.

ECONOMICS

Nuclear power will succeed in the long run only if it has a lower cost than competing technologies. This is especially true as electricity markets become progressively less subject to economic regulation in many parts of the world. We constructed a model to evaluate the real cost of electricity from nuclear power versus pulverized coal plants and natural gas combined cycle plants (at various projected levels of real lifetime prices for natural gas), over their economic lives. These technologies are most widely used today and, absent a carbon tax or its equivalent, are less expensive than many renewable technologies. Our "merchant" cost model uses assumptions that commercial investors would be expected to use today, with parameters based on actual experience rather than engineering estimates of what might be achieved under ideal conditions; it compares the constant or "levelized" price of electricity over the life of a power plant that would be necessary to cover all operating expenses and taxes and provide an acceptable return to investors. The comparative figures given below assume 85% capacity factor and a 40-year economic life for the nuclear plant, reflect economic conditions in the U.S, and consider a range of projected improvements in nuclear cost factors. (See Table.)

Comparative Power Costs

CASE (Year 2002 $)	REAL LEVELIZED COST Cents/kWe-hr
Nuclear (LWR)	6.7
+ Reduce construction cost 25%	5.5
+ Reduce construction time 5 to 4 years	5.3
+ Further reduce O&M to 13 mills/kWe-hr	5.1
+ Reduce cost of capital to gas/coal	4.2
Pulverized Coal	4.2
CCGT[a] (low gas prices, $3.77/MCF)	3.8
CCGT (moderate gas prices, $4.42/MCF)	4.1
CCGT (high gas prices, $6.72/MCF)	5.6

a. Gas costs reflect real, levelized acquisition cost per thousand cubic feet (MCF) over the economic life of the project.

We judge the indicated cost improvements for nuclear power to be plausible, but not proven. The model results make clear why electricity produced from new nuclear power plants today is not competitive with electricity produced from coal or natural gas-fueled CCGT plants with low or moderate gas prices, unless *all* cost improvements for nuclear power are realized. The cost comparison becomes worse for nuclear if the capacity factor falls. It is also important to emphasize that the nuclear cost structure is driven by high up-front capital costs, while the natural gas cost driver is the fuel cost; coal lies in between nuclear and natural gas with respect to both fuel and capital costs.

Power Costs with Carbon Taxes

CARBON TAX CASES LEVELIZED ELECTRICITY COST cents/kWe-hr	$50/tonne C	$100/tonne C	$200/tonne C
Coal	5.4	6.6	9.0
Gas (low)	4.3	4.8	5.9
Gas (moderate)	4.7	5.2	6.2
Gas (high)	6.1	6.7	7.7

Nuclear does become more competitive by comparison if the social cost of carbon emissions is internalized, for example through a carbon tax or an equivalent "cap and trade" system. Under the assumption that the costs of carbon emissions are imposed, the accompanying table illustrates the impact on the competitive costs for different power sources, for emission costs in the range of $50 to $200/tonne carbon. (See Table.) The ultimate cost will depend on both societal choices (such as how much carbon dioxide emission to permit) and technology developments, such as the cost and feasibility of large-scale carbon capture and long-term sequestration. Clearly, costs in the range of $100 to $200/tonne C would significantly affect the relative cost competitiveness of coal, natural gas, and nuclear electricity generation.

The carbon-free nature of nuclear power argues for government action to encourage maintenance of the nuclear option, particularly in light of the regulatory uncertainties facing the use of nuclear power and the unwillingness of investors to bear the risk of introducing a new generation of nuclear facilities with their high capital costs.

We recommend three actions to improve the economic viability of nuclear power:

The government should cost share for site banking for a number of plants, certification of new plant designs by the Nuclear Regulatory Commission, and combined construction and operating licenses for plants built immediately or in the future; we support U.S. Department of Energy initiatives on these subjects.

The government should recognize nuclear as carbon-free and include new nuclear plants as an eligible option in any federal or state mandatory renewable energy portfolio (i.e., a "carbon-free" portfolio) standard.

The government should provide a modest subsidy for a small set of "first mover" commercial nuclear plants to demonstrate cost and regulatory feasibility in the form of a production tax credit.

We propose a production tax credit of up to $200 per kWe of the construction cost of up to 10 "first mover" plants. This benefit might be paid out at about 1.7 cents per kWe-hr, over a year and a half of full-power plant operation. We prefer the production tax credit mechanism because it offers the greatest incentive for projects to be completed and because it can be extended to other carbon free electricity technologies, for example renewables, (wind currently enjoys a 1.7 cents per kWe-hr tax credit for ten years) and coal with carbon capture and sequestration. The credit of 1.7 cents per kWe- hr is equivalent to a credit of $70 per avoided metric ton of carbon if the electricity were to have come from coal plants (or $160 from natural gas plants). Of course, the carbon emission reduction would then continue without public assistance for the plant life (perhaps 60 years for nuclear). If no new nuclear plant is built, the government will not pay a subsidy.

These actions will be effective in stimulating additional investment in nuclear generating capacity if, and only if, the industry can live up to its own expectations of being able to reduce considerably capital costs for new plants.

Advanced fuel cycles add considerably to the cost of nuclear electricity. We considered reprocessing and one-pass fuel recycle with current technology, and found the fuel cost, including waste storage and disposal charges, to be about 4.5 times the fuel cost of the once-through cycle. Thus use of advanced fuel cycles imposes a significant economic penalty on nuclear power.

SAFETY

We believe the safety standard for the global growth scenario should maintain today's standard of less than one serious release of radioactivity accident for 50 years from all fuel cycle activity. This standard implies a ten-fold reduction in the expected frequency of serious reactor core accidents, from 10^{-4}/reactor year to 10^{-5}/reactor year. This reactor safety standard should be possible to achieve in new light water reactor plants that make use of advanced safety designs. International adherence to such a standard is important, because an accident in any country will influence public attitudes everywhere. The extent to which nuclear facilities should be hardened to possible terrorist attack has yet to be resolved.

We do not believe there is a nuclear plant design that is totally risk free. In part, this is due to technical possibilities; in part due to workforce issues. Safe operation requires effective regulation, a management committed to safety, and a skilled work force.

The high temperature gas-cooled reactor is an interesting candidate for reactor research and development because there is already some experience with this system, although not all of it is favorable. This reactor design offers safety advantages because the high heat capacity of the core and fuel offers longer response times and precludes excessive temperatures that might lead to release of fission products; it also has an advantage compared to light water reactors in terms of proliferation resistance.

These actions will be effective in stimulating additional investment in nuclear generating capacity if, and only if, the industry can live up to its own expectations of being able to reduce considerably overnight capital costs for new plants.

Because of the accidents at Three Mile Island in 1979 and Chernobyl in 1986, a great deal of attention has focused on reactor safety. However, the safety record of reprocessing plants is not good, and there has been little safety analysis of fuel cycle facilities using, for example, the probabilistic risk assessment method. More work is needed here.

Our principal recommendation on safety is:

The government should, as part of its near-term R&D program, develop more fully the capabilities to analyze life-cycle health and safety impacts of fuel cycle facilities and focus reactor development on options that can achieve enhanced safety standards and are deployable within a couple of decades.

WASTE MANAGEMENT

The management and disposal of high-level radioactive spent fuel from the nuclear fuel cycle is one of the most intractable problems facing the nuclear power industry throughout the world. No country has yet successfully implemented a system for disposing of this waste. We concur with the many independent expert reviews that have concluded that geologic repositories will be capable of safely isolating the waste from the biosphere. However, implementation of this method is a highly demanding task that will place great stress on operating, regulatory, and political institutions.

We do not believe a convincing case can be made, on the basis of waste management considerations alone, that the benefits of advanced, closed fuel cycles will outweigh the attendant safety, environmental, and security risks and economic costs.

For fifteen years the U.S. high-level waste management program has focused almost exclusively on the proposed repository site at Yucca Mountain in Nevada. Although the successful commissioning of the Yucca Mountain repository would be a significant step towards the secure disposal of nuclear waste, we believe that a broader, strategically balanced nuclear waste program is needed to prepare the way for a possible major expansion of the nuclear power sector in the U.S. and overseas.

The global growth scenario, based on the once-through fuel cycle, would require multiple disposal facilities by the year 2050. To dispose of the spent fuel from a steady state deployment of one thousand 1 GWe reactors of the light water type, new repository capacity equal to the nominal storage capacity of Yucca Mountain would have to be created somewhere in the world every three to four years. This requirement, along with the desire to reduce long-term risks from the waste, prompts interest in advanced, closed fuel cycles.

These schemes would separate or partition plutonium and other actinides — and possibly certain fission products — from the spent fuel and transmute them into shorter-lived and more benign species. The goals would be to reduce the thermal load from radioactive decay of the waste on the repository, thereby increasing its storage capacity, and to shorten the time for which the waste must be isolated from the biosphere.

We have analyzed the waste management implications of both once-through and closed fuel cycles, taking into account each stage of the fuel cycle and the risks of radiation exposure in both the short and long-term. *We do not believe that a convincing case can be made on the basis of waste management considerations alone that the benefits of partitioning and transmutation will outweigh the attendant safety, environmental, and security risks and economic costs.* Future technology developments could change the balance of expected costs, risks, and benefits. For our fundamental conclusion to change, however, not only would the expected long term risks from geologic repositories have to be significantly higher than those indicated in current assessments, but the incremental costs and short-term safety and environmental risks would have to be greatly reduced relative to current expectations and experience.

We further conclude that waste management strategies in the once-through fuel cycle are potentially available that could yield long-term risk reductions at least as great as those claimed for waste partitioning and transmutation, with fewer short-term risks and lower development and deployment costs. These include both incremental improvements to the current mainstream mined repositories approach and more far-reaching innovations such as deep borehole disposal. Finally, replacing the current ad hoc approach to spent fuel storage at reactor sites with an explicit strategy to store spent fuel for a period of several decades will create additional flexibility in the waste management system.

Our principal recommendations on waste management are:

The DOE should augment its current focus on Yucca Mountain with a balanced long-term waste management R&D program.

A research program should be launched to determine the viability of geologic disposal in deep boreholes within a decade.

A network of centralized facilities for storing spent fuel for several decades should be established in the U.S. and internationally.

NONPROLIFERATION

Nuclear power should not expand unless the risk of proliferation from operation of the commercial nuclear fuel cycle is made acceptably small. We believe that nuclear power can expand as envisioned in our global growth scenario with acceptable incremental proliferation risk, provided that reasonable safeguards are adopted and that deployment of reprocessing and enrichment are restricted. The international community must prevent the acquisition of weapons-usable material, either by diversion (in the case of plutonium) or by misuse of fuel cycle facilities (including related facilities, such as research reactors or hot cells). Responsible governments must control, to the extent possible, the know-how relevant to produce and process either highly enriched uranium (enrichment technology) or plutonium.

Three issues are of particular concern: existing stocks of *separated* plutonium around the world that are directly usable for weapons; nuclear facilities, for example in Russia, with inadequate controls; and transfer of technology, especially enrichment and reprocessing technology, that brings nations closer to a nuclear weapons capability. The proliferation risk of the global growth scenario is underlined by the likelihood that use of nuclear power would be introduced and expanded in many countries in different security circumstances.

Nuclear power should not expand unless the risk of proliferation from operation of the commercial nuclear fuel cycle is made acceptably small.

An international response is required to reduce the proliferation risk. The response should:

- re-appraise and strengthen the institutional underpinnings of the IAEA safeguards regime in the near term, including sanctions;
- guide nuclear fuel cycle development in ways that reinforce shared nonproliferation objectives.

Accordingly, we recommend:

The International Atomic Energy Agency (IAEA) should focus overwhelmingly on its safeguards function and should be given the authority to carry out inspections beyond declared facilities to suspected illicit facilities;

Greater attention must be given to the proliferation risks at the front end of the fuel cycle from enrichment technologies;

IAEA safeguards should move to an approach based on continuous materials protection, control and accounting using surveillance and containment systems, both in facilities and during transportation, and should implement safeguards in a risk-based framework keyed to fuel cycle activity;

Fuel cycle analysis, research, development, and demonstration efforts must include explicit analysis of proliferation risks and measures defined to minimize proliferation risks;

International spent fuel storage has significant nonproliferation benefits for the growth scenario and should be negotiated promptly and implemented over the next decade.

ANALYSIS, RESEARCH, DEVELOPMENT, AND DEMONSTRATION PROGRAM

The U.S. Department of Energy (DOE) analysis, research, development, and demonstration (ARD&D) program should support the technology path leading to the global growth scenario and include diverse activities that balance risk and time scales, in pursuit of the strategic objective of preserving the nuclear option. *For technical, economic, safety, and public acceptance reasons, the highest priority in fuel cycle ARD&D, deserving first call on available funds, lies with efforts that enable robust deployment of the once-through fuel cycle*. The current DOE program does not have this focus.

Every industry in the United States develops basic analytical models and tools such as spreadsheets that allow firms, investors, policy makers, and regulators to understand how changes in the parameters of a process will affect the performance and cost of that process. But we have been struck throughout our study by the absence of such models and simulation tools that permit in-depth, quantitative analysis of trade-offs between different reactor and fuel cycle choices, with respect to all key criteria. The analysis we have seen is based on point designs and does not incorporate information about the cost and performance of operating commercial nuclear facilities. Such modeling and analysis under a wide variety of scenarios, for both open and closed fuel cycles, will be useful to the industry and investors, as well as to international discussions about the desirability about different fuel cycle paths.

We call on the Department of Energy, perhaps in collaboration with other countries, to establish a major project for the modeling, analysis, and simulation of commercial nuclear power systems — The Nuclear System Modeling Project. This project should provide a foundation for the accumulation of information about how variations in the operation of plants and other parts of the fuel cycle affect costs, safety, waste, and proliferation resistance characteristics. The models and analysis should be based on real engineering data and, wherever possible, practical experience. This project is technically demanding and will require many years and considerable resources to be carried out successfully.

For technical, economic, safety, and public acceptance reasons, the highest priority in fuel cycle R&D, deserving first call on available funds, lies with efforts that enable robust deployment of the once-through fuel cycle.

We believe that development of advanced nuclear technologies — either fast reactors or advanced fuel cycles employing reprocessing – should await the results of the *Nuclear System Modeling Project* we have proposed above. Our analysis makes clear that there is ample time for the project to compile the necessary engineering and economic analyses and data before undertaking expensive development programs, even if the project should take a decade to complete. Expensive programs that plan for the development or deployment of commercial reprocessing based on any existing advanced fuel cycle technologies are simply not justified on the basis of cost, or the unproven safety, proliferation risk, and waste properties of a closed cycle compared to the once-through cycle. Reactor concept evaluation should be part of the Nuclear System Modeling Project.

On the other hand, we support a modest laboratory scale research and analysis program on *new* separation methods and associated fuel forms, with the objective of learning about approaches that emphasize lower cost and more proliferation resistance. These data can be important inputs to advanced fuel cycle analysis and simulation and thus help prioritize future development programs.

The modeling project's research and analysis effort should only encompass technology pathways that do not produce weapons-usable material during normal operation (for example, by leaving some uranium, fission products, and/or minor actinides with the recycled plutonium). *The closed fuel cycle currently practiced in Western Europe and Japan, known as PUREX/MOX, does not meet this criterion*. There are advanced closed fuel cycle concepts involving combinations of reactor, fuel form, and separations technology that satisfy these conditions and, with appropriate institutional arrangements, can have significantly better proliferation resistance than the PUREX/MOX fuel cycle, and perhaps approach that of the open fuel cycle. Accordingly, the governments of nuclear supplier countries should discourage other nations from developing and deploying the PUREX/MOX fuel cycle.

Government R&D support for advanced design LWRs and for the High Temperature Gas Reactor (HTGR) is justified because these are the two reactor types that are most likely to play a role in any nuclear expansion. R&D support for advanced design LWRs should focus on measures that reduce construction and operating cost. Because the High Temperature Gas Reactor (HTGR) has potential advantages with respect to safety, proliferation resistance, modularity and efficiency, government research and limited development support to resolve key uncertainties, for example, the performance of HTGR fuel forms in reactors and gas power conversion cycle components, is warranted.

Waste management also calls for a significant, and redirected, ARD&D program. The DOE waste program, understandably, has been singularly focused for the past several years on the Yucca Mountain project. We believe DOE must broaden its waste R&D effort or run the risk of being unable to rigorously defend its choices for waste disposal sites. More attention needs to be given to the characterization of waste forms and engineered barriers, followed by development and testing of engineered barrier systems. We believe deep boreholes, as an alternative to mined repositories, should be aggressively pursued. These issues are inherently of international interest in the growth scenario and should be pursued in such a context.

The closed fuel cycle currently practiced in Western Europe and Japan, known as PUREX/MOX, does not meet this nonproliferation criterion.

There is opportunity for international cooperation in this ARD&D program on safety, waste, and the Nuclear System Modeling Project. A particularly pertinent effort is the development, deployment, and operation of a word wide materials protection, control, and accounting tracking system. There is no currently suitable international organization for this development task. A possible approach lies with the G-8 as a guiding body.

Our global growth scenario envisions an open fuel cycle architecture at least until mid-century or so, with the advanced closed fuel cycles possibly deployed later, but only if significant improvements are realized through research. The principal driver of this conclusion is our judgment that natural uranium ore is available at reasonable prices to support the open cycle at least to late in the century in a scenario of substantial expansion. This gives the open cycle clear economic advantage with proliferation resistance an important additional feature. The DOE should undertake a global uranium resource evaluation program to determine with greater confidence the uranium resource base around the world.

Accordingly, we recommend:

The U.S. Department of Energy should focus its R&D program on the once-through fuel cycle;

The U.S. Department of Energy should establish a Nuclear System Modeling project to carryout the analysis, research, simulation, and collection of engineering data needed to evaluate all fuel cycles from the viewpoint of cost, safety, waste management, and proliferation resistance;

The U.S. Department of Energy should undertake an international uranium resource evaluation program;

The U.S. Department of Energy should broaden its waste management R&D program;

The U.S. Department of Energy should support R&D that reduces Light Water Reactor (LWR) costs and for development of the HTGR for electricity application.

We believe that the ARD&D program proposed here is aligned with the strategic objective of enabling a credible growth scenario over the next several decades. Such a ARD&D program requires incremental budgets of almost $400 million per year over the next 5 years, and at least $460 million per year for the 5-10 year period.

Chapter 2 — Background and Purpose of This Study

In 2000 nuclear power produced about 17% of the world's electricity from 442 commercial reactors in 31 countries. The United States has the largest deployment, with 104 operating reactors producing 20% of the country's electricity, followed by France, Japan, Germany, Russia, and South Korea. The reliability of these plants has improved considerably in recent years (for example, capacity factors of U.S. nuclear reactors have achieved 90%), and many will have their originally expected operating lives extended significantly. Nuclear power is clearly an important source of electricity in the United States and the world.

If current policies continue, however, nuclear power is likely to decline gradually and conceivably disappear in this century from the world's electricity supply portfolio. We believe removing nuclear power as a supply option would be a mistake at this time. The primary reason is that nuclear power is an important source of electricity that does not rely on fossil fuel and hence does not produce greenhouse gas emissions. This is the primary motivation for our examination for an inter-connected set of issues that will challenge nations individually and collectively over the next century. The issues are:

- reducing atmospheric pollution and emissions of greenhouse gases;
- meeting dramatically increased energy, and especially electricity, demand throughout the industrialized and developing world; and
- assuring security and minimizing conflict associated with energy supply.

Our study undertakes to:

- describe the characteristics of a nuclear power infrastructure that would make a significant contribution to reducing CO_2 emissions;
- identify the issues that must be addressed if nuclear power is to make a contribution on this scale; and
- outline the needed program of analysis, research, development, and demonstration.

GLOBAL WARMING

Most developed countries are in the early stages of implementing policies to stabilize and ultimately reduce greenhouse gas emissions and the attendant global warming. The scientific consensus about the risks of further significant increases in atmospheric greenhouse gas concentrations grows steadily stronger and more widely endorsed. This consensus underlies a strong impetus for governmental actions that prepare the ground for meeting possibly stringent CO_2 emission constraints in the decades ahead, specifically global emission levels comparable to or below those of today, despite a considerable increase in energy production and use. Developing countries will need to limit the growth of greenhouse gas emissions while their energy consumption increases dramatically. For example, if atmospheric concentration of CO_2 is not allowed to exceed twice its pre-industrial value, then CO_2 emissions in the 21st century will need to be held to half the cumulative total expected under a "business as usual" trajectory,[1] and the annual emission rate would eventually need to fall well below the 2000 value. While our focus is on global warming because of its overwhelming international implications, we recognize that reduction in other emissions from fossil fuel combustion would have important regional and local benefits for clean air.

We believe that the United States will eventually join with other developed countries in the effort to reduce greenhouse gas emissions, even if the mechanisms for doing so are uncertain for the moment. Developing countries – certainly the large ones, such as China, India, Pakistan, Brazil, and Indonesia – must ultimately be party to this effort if it is to succeed. Achieving the reductions in greenhouse gas emissions likely to be required will be a major technical and economic challenge to both developed and developing countries that will persist for many decades into the future.

The power sector contributes about a third of greenhouse gas emissions worldwide. The Energy Information Administration (EIA) of the U.S. Department of Energy projects that, in the absence of CO_2-control policies and technologies, electricity's share of global emissions of greenhouse gases (CO_2 and others) will climb to over 40% by 2020. In the United States, almost 90% of the carbon emissions from electricity generation come from coal-fired generation, even though this accounts for only 52% of the electricity. (About 29% of United States electricity comes from carbon-free nuclear and renewables-based generation; about 19% comes from natural-gas-fired and oil-fired generation, but both of these fuels release less carbon per kilowatt-hour than coal-fired generation does.)

There are few realistic options to reduce significantly carbon emissions from electricity generation (besides lowering standards of living):

- ☐ increased efficiency in electricity end-use and generation;
- ☐ increased use of renewable energy technologies (e.g., wind, solar, biomass, and geothermal);
- ☐ introduction of carbon capture and sequestration at fossil-fueled (especially coal) power plants on a massive scale; and
- ☐ increased use of nuclear fission power reactors (and possibly fusion at a later date).

As we have argued in Chapter 1, *our view is that it would be a mistake to exclude at this time any of these four basic options as a possibly important part of an overall carbon emissions management strategy*. Each of the options presents technical, economic, environmental, political, and human behavioral issues that make their ultimate market penetration uncertain.

Nuclear power is a special case, however. If current trends continue, nuclear power will gradually decrease and perhaps even disappear as part of the global energy portfolio, thus failing to make any long-term contribution to reducing greenhouse gas emissions. Few nuclear power plants are under construction worldwide, and of those, most are being built in a small number of developing countries or developed countries in East Asia.[2] In most developed countries, the use of nuclear power is not expected to expand and, in many of these countries, including the United States, nuclear power has been explicitly excluded from policies to stabilize and reduce carbon emissions (e.g., direct and tax subsidies for renewable energy and energy conservation, high mandated purchase prices for renewable energy, renewable energy portfolio standards). In Britain, nuclear power plants pay a "carbon tax," even though they have essentially no CO_2 emissions. We believe that a more objective approach will have a better chance at meeting the global warming challenge. Indeed, it is likely that our energy future will exploit *all* of the four options to one degree or another. This study addresses the issues associated with maintaining the nuclear power option.

ELECTRICITY DEMAND

The U.S. National Academy of Engineering named electrification as the premier engineering achievement of the twentieth century[3]. This is a remarkable statement for the century of lasers, computers, airplanes, and other ubiquitous and important technologies and is indicative of the extraordinary impact of electricity in improving the quality of people's lives. Accordingly, it should not be surprising that global electricity use is expected to increase dramatically in the years ahead, even taking into account improvements in end use efficiency. Growth in electricity use is expected especially in developing countries, as they strive to meet basic needs and to modernize and industrialize their economies.

The U.S. Department of Energy's EIA projects a 75% increase in global electricity use in two decades, from 2000 to 2020. By mid-century, a threefold increase or more is credible and, indeed, expected. Table 2.1 gives the growth rate for electricity use in different regions of the world as anticipated in the EIA "business-as-usual" projections to the year 2020.[4]

There is a strong correlation between electricity consumption per capita and the United Nations "human development index" (HDI), which combines indicators of health, education, and economic prosperity.[5] Industrialized countries have an HDI above 0.9 (on a scale of 0 to 1) and per capita energy consumption above 4000 kWe-hrs.

Large developing countries, such as China, India, Pakistan, and Indonesia, are well below the industrialized country HDI and aspire to advance by rapid economic growth. Overall, energy consumption per capita in the developing world is currently less than a fifth of that in the developed world. Unless provided with assistance or incentives, these developing nations are likely to seek the lowest cost supply alternatives that can meet their growing industrial and consumer demand for electricity. This prospect clearly raises the specter of substantially increased greenhouse gas emissions, since coal is likely to be an economic choice for many developing countries, e.g. China and India. *How these developing countries meet their electricity demand is of central interest to the discussion of global warming, since over time their choices will influence global emissions levels more than measures taken by the developed world*. Greater electricity consumption is desirable because it accompanies social and economic advance, but we want the electricity production to take place in an economic and environmentally acceptable manner.

Table 2.1 Anticipated Growth of Electricity (billion kWe-h)[4]

REGION (billion kWe-h)	1999	2020	GROWTH RATE %
Industrialized	7,500	10,900	1.8
(US)	3,200	4,800	1.9
FSU	1,500	2,100	1.8
Developing	3,900	9,200	4.2
Total World	12,800	22,200	2.7

The attractiveness of nuclear power as an option will be determined by many country-specific factors. To understand how much nuclear power would be needed to make a significant contribution to reducing CO_2 emissions by 2050, and where it might be deployed, we present, in Appendix 2, a simple scenario for electricity growth over the next fifty years. The scenario is not based on economic forecasting, but on a model of what electricity growth could be as countries attempt to raise individual living standards to acceptable levels within credible growth constraints. The model assumes a modest 1%/year annual growth in per capita electricity consumption for developed countries and a growth rate for developing countries that takes them to 4000 kWe-hrs/person/year in 2050 (i.e., we determine the growth rate as an outcome). Population projections are those currently provided by the United Nations. The one additional constraint in the scenario is that the annual growth rate in total electricity production for any country is capped at 4.7%; this is one half percent above EIA's projected electricity growth rate for the developing world overall up to 2020. Sustaining a 4.7%/year growth rate for fifty years yields a factor of ten increase; although within the realm of possibility with appropriate policies and sufficient resource investment, this cap on total growth represents a very ambitious target for any individual developing country. Within this scenario, global electricity production is slightly below the EIA reference in 2020 and about a factor of three greater in 2050 than it is today. The implications of this scenario for four categories of nations are described below.

Developed countries. Among the major developed countries, the United States is unique in having a projected large increase in population and a concomitant large increase in total electricity demand. If the global deployment of nuclear power is to grow substantially by mid-century, the United States almost certainly must be a major participant. Nuclear power growth is unlikely to be very large in other key developed countries, such as Japan (with an anticipated population decline) or France (with a stable population and a power sector already dominated by nuclear power).

More advanced developing countries. Countries such as China, Brazil, Mexico, and Iran can reach the 4000 kWe-hrs/person/year benchmark with annual growth rates of electricity consumption in the 2%-3% range. Although improved business, regulatory, financial, political, and other conditions may be needed, these countries would likely be very important for an expanded nuclear power scenario. By 2050, they will have large urban populations (above 85%), an important factor favoring the introduction of large base load plants. This model is, of course, subject to country-specific caveats; for example, Iran has abundant natural gas supplies, so its pursuit of nuclear power logically raises proliferation concerns. Collectively, countries in this group have relatively little nuclear power today but could turn to nuclear power to meet a fraction of their future electricity supply needs, as South Korea has done.

Less advanced developing countries. Countries such as India, Pakistan, Indonesia, Philippines, and Vietnam (with a combined projected population of 2.5 billion in 2050) may, with considerable progress in their political, legal, financial, and regulatory regimes and an associated increase in domestic and foreign investment in their energy sectors, reach 2000-3000 kWe-hrs/person/year by mid-century. This will be a tall order. Nuclear power may account for part of the dramatic increase in electricity supply called for in these countries (India is an exception in that it already has fourteen units), but pursuing such a capital- and management-intensive technology will prove challenging. In many cases, proliferation concern – the concern that the commercial nuclear fuel cycle will be used as a source of materials and/or technology that will lead to proliferation of nuclear weapons – will accompany development of substantial nuclear technology infrastructures.

Least advanced developing countries. Many large developing countries, with a particular concentration in Africa, cannot come close to the per capita benchmark within economically credible scenarios. These countries are not good candidates for nuclear power, barring an unforeseen breakthrough in technology and capital requirements.

In sum, electricity utilization is likely to increase significantly worldwide over the next half-century, requiring a major investment in both replacement and expansion of generating capacity. Much of the expansion will take place in the developing world. Selected developed countries will be central to a major increase in nuclear power, but large parts of the developing world are unlikely participants. If developing nations do adopt nuclear power, all nations of the world will have an interest in how these countries regulate their nuclear enterprise with respect to reactor and fuel cycle safety, transportation of nuclear materials, waste disposal, and especially proliferation safeguards.

SECURITY

Yet another reason for thinking about the nuclear option — national security — is not new. The dependence of the developed world on oil from the Middle East, an unstable region of the world, has long presented a risk to the economies of the United States and other countries that depend on imported oil, such as Japan, Germany, and France. The United States' dependence is linked principally to fuel for the transportation sector, but many other countries rely on oil for significant power generation. Nuclear power offers one option for reducing this dependence.

Within the time horizon addressed in this study, however, the national security implications of expanded nuclear power may be even more significant with respect to natural gas, which displays the same lack of geographic correlation between supply and demand that has defined the geopolitical landscape for oil. It is likely that many nations, including the United States, may import large quantities of LNG or liquids from gas, produced from stranded gas in diverse regions of the world.

There is another national security dimension to nuclear power. Combating nuclear proliferation is one of our most important foreign policy objectives. There is no doubt about the great risk to the security of the United States and the rest of the world that the spread of nuclear weapons to other states and perhaps non-state actors would bring. So there is a major security interest in how all aspects of nuclear commerce develop around the world. For example, the extensive U.S. "Cooperative Threat Reduction program,"[6] provides assistance to Russia for the purpose of improving their efforts to protect their nuclear weapons and nuclear explosive materials against theft.[7] On the other hand, there is considerable tension between the United States and Russia created by Russian assistance to Iran on commercial nuclear power, especially since Iran is awash in natural gas.

Indeed, it is worth recalling that the unresolved nuclear fuel cycle "schism" of the 1970s between the United States and its European and Japanese allies stemmed from nonproliferation concerns. In the Ford and Carter administrations, the United States stopped the recycling of plutonium in commercial reactors because of proliferation risks associated with a "plutonium economy." The hope that others would emulate this policy was not realized, as energy resource-poor countries, such as France and Japan, evaluated the balance of risks differently. As countries look to shape today's nuclear fuel cycle policy and R&D decisions in the context of the world environmental, economic development, and security needs of the next fifty years, finding a common path among the G-8 and others can itself contribute significantly to managing proliferation concerns. The expansion of nuclear power, should it occur, will raise proliferation concerns that call for ongoing American engagement in nuclear fuel cycle issues independent of nuclear power's level of contribution to domestic electricity generation.

THE CHALLENGES OF NUCLEAR POWER EXPANSION

Despite the strong rationale for reducing greenhouse gas emissions that contribute to global warming, for meeting increasing demand for electricity, and for improving the national security aspects of energy supply, the EIA's "business-as-usual" projection for nuclear power indicates a mere 5% increase in 2020, even as world electricity use increases by 75%. After 2020, if significant investments are not made, nuclear power supply would decline as existing reactors are retired. EIA projects significant increases in nuclear generated electricity in China, Japan, and South Korea, largely offsetting decreases in the United States and Western Europe. In the United States, the last nuclear plant order was in 1979. There is considerable anti-nuclear sentiment in Europe: Belgium, Germany, the Netherlands, and Sweden are officially committed to phasing out nuclear power gradually; and there is public opposition to nuclear power in Japan and Taiwan. To be sure, several countries are still on a path to construct new operating units — South Korea, Finland, India, and Russia are examples — and China may yet commit to substantial new nuclear plant construction.

There are several reasons why nuclear power has not met the expectations for capacity growth projected several decades ago. One factor is that the public perception of nuclear energy is unfavorable, in part due to concern about effects of radiation that the public associates with nuclear energy. More importantly, the adverse impression derives from real and unique problems presented by this technology. These problems are:

Unfavorable economics. Most operating nuclear plants are economical to operate when costs going forward are considered, i.e. when sunk capital and construction costs are ignored. However, new plants appear to be more expensive than alternate sources of base load generation, notably coal and natural gas fired electricity generation, when both capital and operating costs are taken into account.

Coal plants have capital costs intermediate between those of gas and nuclear. Even with SO_2 and NO_x controls that meet U.S. new source performance standards, new coal plants are widely perceived to be less costly than nuclear plants. However, if CO_2 emissions were in the future to become subject to control and a significant "price" placed on emissions, the relative economics could become much more favorable to nuclear power.

Perceived adverse safety, environmental, and health effects. After the 1979 accident at Three Mile Island in Harrisburg, Pennsylvania and the 1986 accident at Chernobyl in the Soviet Union, public concern about reactor safety increased substantially. The 1999 accident at the Tokai-

Mura plant underscored safety concerns about the nuclear fuel cycle outside of the reactor. There is also concern about transportation of nuclear materials, and waste management. The September 11, 2001 terrorist attack on the World Trade Center and the Pentagon have heightened concerns about the vulnerability of nuclear power stations and other facilities, especially spent fuel storage pools, to terrorist attack. There is concern about radiation exposure of citizens and workers from activities of the industry despite good regulation and health records. There are significant environmental impacts, ranging from long-term waste disposal to the handling and disposal of toxic chemical wastes associated with the nuclear fuel cycle.

Proliferation. The possibility exists that nations wishing to acquire or enhance a nuclear weapons capability will use commercial nuclear power as a source of technological know-how or nuclear weapons usable material, notably plutonium. Although this has not proved to be the preferred pathway to nuclear weapons capability, the possession of a complete nuclear fuel cycle, including enrichment, fuel fabrication, reactor operation, and reprocessing, certainly moves any nation closer to obtaining such a capability. The key step for achieving nuclear weapons capability is acquisition of sufficient weapons-usable fissionable material, either high-enriched uranium or plutonium. Unfortunately, reprocessing of spent fuel for the fuel cycle operation in Europe, Russia, and Japan has led to the accumulation of about 200 tonnes of separated plutonium. The associated risks have been viewed with increased alarm since the 9/11 events that demonstrated the reach of international terrorism. Radiation exposure from spent fuel that is not reprocessed is a strong, but not certain, barrier to theft and misuse.

Difficulty of waste management. There are many radioactive waste streams created in various parts of the nuclear fuel cycle. What deservedly receives the most attention is the high level waste containing the fission products and/or transuranic (TRU) elements created during energy generation. The spent fuel from nuclear reactors contains radioactive material that presents health and environmental risks that persist for tens of thousands of years. At present, no nation has successfully demonstrated a disposal system for these nuclear wastes. On the other hand, Finland has decided on a path to manage spent fuel, and the United States has decided to proceed with licensing of Yucca Mountain as a geological repository. At the same time, many of the discussions surrounding alternative reactors and fuel cycles are motivated by a desire to reduce high-level waste management challenges.

The potential impact on the public from safety or waste management failure and the link to nuclear explosives technology are unique to nuclear energy among energy supply options. These characteristics and the fact that nuclear is more costly, make it impossible today to make a credible case for the immediate expanded use of nuclear power.

Inevitably, there will be a high degree of government involvement in nuclear power, even in market economies, to regulate safety, waste, and proliferation risk. This is, in itself, another challenge for nuclear power. There is considerable variation in how different countries approach the issues of safety, proliferation, and waste management. This often complicates the role of governments in setting international rules – especially for preventing proliferation, but also for safety and waste management – that serve common interests. Poor safeguarding of nuclear materials or facilities in any nation could result in acquisition of nuclear explosives by a rogue state or terrorist group for use in another nation. The Chernobyl accident demonstrated the potential for radioactivity to spread across borders and thus the importance of uniformly high safety standards and advanced safety technologies (such as western reactor containment designs).

Nuclear power’s value as a carbon-free electricity supply technology has also generally not been recognized in government policies. Government policies have focused on targeting renewable energy resources and end-use efficiency improvements through a combination of direct subsidies, tax subsidies, renewable energy portfolio standards, appliance efficiency standards, and other “second best” mechanisms to promote carbon-free supply technologies and to reduce electricity demand. Nuclear power has generally been excluded from these programs. While the European Union will introduce a carbon dioxide emissions trading system in a few years, countries have not yet turned to broad policies to internalize the social costs of carbon emissions that would provide incentives for investment in all carbon free electricity supply or energy efficiency technologies, including nuclear power. Thus nuclear power does not compete on a level playing field and, from this perspective, is presently being discriminated against in policies designed to respond to the challenge of reducing carbon dioxide emissions.

Given these difficulties, it is fair to ask whether nuclear energy can ever recapture its attractiveness as a major energy supply option. However, this is not the question we seek to address. The answer to such a question necessarily depends on how societies and technology evolve (economic growth, electricity demand, fuel prices, environmental constraints, premium attached to energy security, the cost of alternatives such as renewables, new technologies such as fusion).

The difficulties facing nuclear power should not, at this time, rule it out as one of a small number of options that may be attractive to exercise in the future, as countries develop responses to the energy and environmental challenges of this century. *We believe that it is important for governments to adopt policies that enable the full range of significant options available. Nuclear is one of those options.* Whether it is an option that will eventually be exercised will depend on many unknown contingencies.

Given the difficulties that confront nuclear power, the effort required to overcome them is justified only if nuclear power potentially can make a significant impact on the major challenges of global warming, electric supply, and security. That is, for nuclear power to merit strategic focus and sustaining actions on the part of government , there must also be a commitment to significant expansion of nuclear power that will sustain and perhaps modestly increase its share of global electricity generation, even as use of electricity multiplies.

NOTES

1. T.M.L. Wigley, "Stabilization of greenhouse gas concentrations," in *U.S. policy on climate change: What next,?* Aspen Institute, Washington D.C., 2002.
2. In 2003, five new units are expected to come into operation: one in the Czech Republic, two in China, and two in South Korea. An additional 18 plants are under construction worldwide, primarily in China, Taiwan, India, Japan, and South Korea.
3. National Academy of Engineering website http://www.greatachievments.org/
4. U.S. Department of Energy, Energy Information Administration (EIS) International Energy Outlook 2002.
5. S. G. Benka, "The Energy Challenges," Physics Today (April 2002) p. 38.
6. This is the Nunn-Lugar-Domenici program. See " DOE's non-proliferation programs with Russia," Co- chairs Howard Baker and Lloyd Cutler, January 10, 2001, The Secretary of Energy Advisory Board, U.S. DOE.
7. For a recent report card, see M. Bunn, A. Wier, and J.P. Holdren, "*Controlling nuclear warheads and materials,*" Nuclear Threat Initiative, Washington, D.C., March 2003.

Chapter 3 — Outline of the Study

Our study makes two assumptions: First, as discussed in Chapter 1, that *nuclear energy is an important energy supply option for the future, but that exercising the option for significant deployment requires that the four significant challenges — cost, safety, waste, and proliferation — must be addressed and overcome*. Second, as discussed in Chapter 2, *that the public and private sectors can justify devoting the resources necessary to overcome these four challenges only if there is some reasonable possibility for major benefit to society* from having this option available in the future.

Therefore, we must consider large-scale deployment of nuclear power as a possible outcome and understand fully the ramifications of turning to nuclear power to provide a significant source of non-carbon electricity supply. From a public policy perspective, the scenarios that merit analysis are either a large-scale deployment or a phase-out of nuclear power over the next half-century. We stress that our approach is to evaluate expansion of nuclear energy as an *option* possibly needed in the future to meet a significant fraction of world electricity demand while addressing global environmental challenges. We are *not* declaring a specific goal for a particular time. Our evaluation criteria are:

- favorable economics;
- effective waste disposal;
- high proliferation resistance; and
- safe operation of all aspects of the fuel cycle.

To undertake this evaluation we need to establish a point of reference for nuclear deployment that might be realized 50 years from now. To set this point of reference, we stipulate as the basis of a scenario that *nuclear energy will retain or increase its current share of electricity generation at mid-century*.[1] The projected growth rate of electricity over a half century period is uncertain. The average rate of growth will depend importantly on several variables, notably the rate of economic growth and the price of electricity. A range of possibilities[2] is presented in Table 3.1.

Table 3.1 Alternative Reference Points for Nuclear Deployment in 2050 in GWe for Different Assumptions about Electricity Growth Rates and Nuclear Market Share[a]

	ALTERNATIVE AVERAGE ELECTRICITY GROWTH RATES 2000–2050 %		
NUCLEAR GENERATION MARKET SHARE %	1.5	2.0	2.5
17	650	838	1,060
20	770	970	1,235
25	880	1,235	1,545

a. We assume the global average capacity factor increases from 75% to 85%.

We adopt 1000 to 1500 GWe as the mid-century reference point range for our study. This is large enough to reveal the challenges that need to be faced to enable the large-scale deployment of nuclear energy. Our analysis and conclusions concerning what we refer to as the global growth scenario, as described in Chapter 1, would not change significantly if this number of deployed reactors were somewhat higher, nor if the time period to reach full operational deployment were extended. We have examined the rate of deployment that would need to occur for a deployment in the range of 1000 to 1500 GWe and note that it is unlikely to proceed in a linear manner; for the next ten to fifteen years, deployment is likely to be slow, and therefore the rate would necessarily accelerate dur-

Table 3.2 Global Growth Scenario

REGION	PROJECTED 2050 GWe CAPACITY	NUCLEAR ELECTRICITY MARKET SHARE	
		2000	2050
Total World	1,000	17%	19%
Developed world	625	23%	29%
U.S.	300		
Europe and Canada	210		
Developed East Asia	115		
FSU	50	16%	23%
Developing world	325	2%	11%
China, India, Pakistan	200		
Indonesia, Brazil, Mexico	75		
Other developing countries	50		

Projected capacity comes from the global electricity demand scenario in Appendix 2, which entails growth in global electricity consumption from 13.6 to 38.7 trillion kWe-hrs from 2000 to 2050 (2.1% annual growth). The market share in 2050 is predicated on 85% capacity factor for nuclear power reactors. Note that China, India, and Pakistan are nuclear weapons capable states. Other developing countries includes as leading contributors Iran, South Africa, Egypt, Thailand, Philippines, and Vietnam.

ing the expansion period. The implied construction rate near the mid-century endpoint of the global growth scenario would be challenging and exceed any rate previously achieved.

The pattern of deployment of nuclear power around the world is also important, especially from the viewpoint of assessing the risks of proliferation. Table 3.2 indicates how 1000 1000MWe (or equivalent smaller reactors) might be distributed around the world in the time period 2030 to 2050. Although this illustrative deployment is highly speculative, it provides a concrete instance of how the global growth scenario might be realized.

Nuclear power expansion on this scale is not likely to happen without United States leadership. It also requires continued European commitment and the initiation or expansion of nuclear power programs in many developing countries around the world. If nuclear deployment on the scale of the global growth scenario were to occur, however, it would avoid a significant amount of carbon dioxide emissions, largely by displacing carbon emitting fossil fuel generation. Today, carbon equivalent emission from human activity totals about 6,500 million metric tonnes per year. This value will probably more than double by 2050, depending on the assumptions made. The 1000 GWe of nuclear power assumed in the global growth scenario would avoid about 800 million tonnes of carbon equivalent if the electricity generation displaced was gas-fired and 1,800 million tonnes of carbon equivalent, if the generation was coal-fired, (assuming no capture and sequestration of CO_2 combustion product). *Thus, the 1000 GWe nuclear program has the potential of displacing 15 - 25% of the anticipated growth in anthropogenic carbon emissions*. In 2050, deployment of 1000 Gwe of nuclear power would generate about 20% of worldwide electricity production, if electricity production grows at 2% per year. Evidently, the global growth scenario would have nuclear power generating significant amounts of electricity that would otherwise likely be generated by fossil fuels.

FUTURE STRUCTURE OF THE NUCLEAR INDUSTRY

Significant expansion of nuclear power has implications for the structure of its supporting nuclear industry infrastructure. In an unregulated economy comprised of private business firms competing in the marketplace, market forces determine the organization and structure of the firms that design, construct, and operate nuclear power plants and supporting fuel cycle facilities. However, because nuclear technology involves significant public issues of safety, waste management, and proliferation, the government has a responsibility to ensure that whatever industry structure develops will facilitate, rather than impede, attention to these issues. The intersection of these public issues and free market operations cannot be handled through minor government regulation, as is possible in some other industries. An additional layer of government involvement stems from the traditional structure of electric utilities as vertically integrated monopolies. Government intervention has been necessary to ensure that the operations of the electric utility industry are efficient and that other public objectives for electricity supply are achieved. We do not today know how the nuclear industry will evolve but we mention issues that we believe are an important determinant of the future success of nuclear power.

The tension between public responsibility and private market operation has been present since the beginning of commercial nuclear power. In the U.S., the assumption was that any private utility was in principle capable of owning and operating a nuclear power plant and should be allowed to do so under appropriate government supervision with regard to safety. Several other countries have followed this route, notably Japan and Germany. In other countries, such as Russia and China, nuclear power has been entirely the responsibility of the central government. Elsewhere the pattern has been mixed. In France, all nuclear plants have been operated by a single state-owned utility, Electricite de France. Similar arrangements have applied in South Korea and Taiwan. In Spain and Sweden a small number of investor-owned utilities have built and operated nuclear power plants.

No arrangement has proved free of tension. In many countries with state-owned electric power monopolies, there has been a move towards privatization and increased competition, while in the U.S. it is widely recognized that in the current environment, small investor-owned utilities operating a single nuclear power plant are more likely to encounter operational problems and to experience higher generating costs.

We do not believe that a single organizational model for nuclear power will be applicable throughout the world. We do believe that industrial organization is an important consideration for the future expansion of nuclear power. To oversimplify, too much government involvement is likely to make nuclear power expensive and uncompetitive, and too little government involvement risks safety, waste, and proliferation problems. International cooperation is also critical for the effective management of these public issues, especially proliferation. Thus, the industrial structure in each country must be compatible with whatever international norms are adopted

The structure of the nuclear industry is also important because of its influence on innovation, productivity, and performance. A necessary condition for the expanded nuclear deployment postulated in the global growth scenario is that nuclear power plants and other nuclear facilities be designed, built, and operated to expectation. This performance, in turn, depends upon sound technological choices, high quality design and construction, and the availability of competent construction project management teams, craft labor, and operating and maintenance personnel. Moreover, the growth of capability in all these categories must occur in the context of a deployment schedule that will be highly uncertain. These are all matters of industrial organization that are critical to the prospects for the expansion of nuclear power but do not happen automatically. Nor is it clear that governments are sufficiently agile or wise to adopt policies that will encourage the proper sequencing of industrial capabilities and needs.

OUTLINE OF THE STUDY

In conducting this study, our first step was to define the character of the global growth scenario, i.e., the nature and size of the fuel cycle necessary for it to function. The results are discussed in Chapter 4.

Our second step was to answer the question: "Is such a mid-century scenario technically, economically and politically credible?" We do this by evaluating how well the global growth scenario can meet the four challenges of cost, safety, waste disposal, and proliferation risk. This is undertaken in Chapters 5 through 8.

Our third step was to consider public attitudes to an expanded nuclear future. Chapter 9 reports on the result of an Internet-based poll that we conducted and its implications.

Our fourth step was to make recommendations that would retain the nuclear option. These recommendations, presented in Part 2 of the report, addresses both domestic and international issues and includes both technical and institutional measures. We identify organizational changes that we believe would increase the chance of success of the effort and decrease the cost. The technical measures involve a sustained and disciplined program of analysis, research, development, and demonstration of various aspects of the nuclear enterprise. We do not seek to establish rigid goals or a fixed timetable for the technical program. The pace of the program should be determined by its technical success in the context of the world energy and environmental outlook. We anticipate that the cost of the technical program would be borne by other countries, as well as by the United States.

This study approach is conditioned by the belief that the nuclear power option makes sense only if possible deployment is quite large, since no small deployment can make a significant contribution to dealing with the greenhouse gas problem. Support for keeping the nuclear power option open will therefore depend on convincing the public and their elected representatives that large-scale deployment can overcome the four challenges. *We believe that establishing a vision for a possible large- scale deployment of nuclear energy that is both technically and politically credible is a necessary condition for gaining public support*. Indeed it is misleading to focus on small increases in nuclear capacity justified by significant CO_2 reduction. Furthermore, small deployments ignore or do not face squarely the challenges that must be overcome for nuclear energy to become a significant contributor to controlling CO_2 emissions.

It will take sustained effort to accomplish the necessary technical and institutional steps needed to make nuclear an attractive energy option. Given the expected evolution of worldwide energy supply and demand, however, we believe there is time to undertake this work . We do not believe that nuclear energy will go forward without such a comprehensive approach. The construction of a few reactors in the short term and a technology driven R&D program is not sufficient. Although R&D is a vital ingredient, a comprehensive program should address all four of the key criteria in order to create a clear and sound vision of the energy future. A similarly broad approach should be applied to all energy supply and end-use efficiency technologies under consideration. A policy directed to a single solution is inadequate. We also recognize that the deployed nuclear fuel cycle will not simply “jump” to a new reality. But, we believe the evolution will be guided by a clear picture of where we are headed and how we will get there.

NOTES

1. Some advocate hydrogen production as an objective for nuclear power. To be economical hydrogen produced by electrolysis of water depends on low cost nuclear power. Hydrogen can also be produced by high temperature thermal cracking with heat provided by a nuclear reactor. This approach is presently highly speculative. Our belief is that if nuclear proves to be an economical choice for electricity production, it *may* prove to be interesting for hydrogen production, whether the production is through electrolysis or high temperature thermal splitting of water. However, if nuclear is not an economical choice for electricity production, it is most unlikely to be used for large-scale production of hydrogen.
2. For example, the EIA projects worldwide electricity growth rate of 2.7% for the period 2000-2020. If we project that this growth rate continues [See Table 3.1.] through mid-century and recognize that about 350 GWe nuclear capacity is currently deployed worldwide (in over 400 units), then the mid-century point of reference for nuclear maintaining its market share is 1325 GWe of deployment in 2050. This deployment might correspond to 1325 reactors, each with capacity of 1000 MWe or more units of smaller rated capacity. There are higher and lower projections of world electricity use. The MIT Emissions Prediction and Policy Analysis (EPPA) project projects an average growth rate between 1995 and 2004 of 1.8% that gives a nuclear deployment of 950 Gwe in 2050, assuming nuclear power retains its market share. If we assume the EIA 2.7% growth rate to 2020 and the lower MIT EPPA 1.8% growth rate between 2020 and 2050, the calculated number is 1164 GWe of nuclear power in 2050.

Chapter 4 — Fuel Cycles

The description of a possible global growth scenario for nuclear power with 1000 or so GWe deployed worldwide must begin with some specification of the nuclear fuel cycles that will be in operation. The nuclear fuel cycle refers to all activities that occur in the production of nuclear energy.

It is important to emphasize that producing nuclear energy requires more than a nuclear reactor steam supply system and the associated turbine-generator equipment required to produce electricity from the heat created by nuclear fission. The process includes ore mining, enrichment, fuel fabrication, waste management and disposal, and finally decontamination and decommissioning of facilities. All steps in the process must be specified, because each involves different technical, economic, safety, and environmental consequences. A vast number of different fuel cycles appear in the literature,[1] and many have been utilized to one degree or another. We review the operating characteristics of a number of these fuel cycles, summarized in Appendix 4.

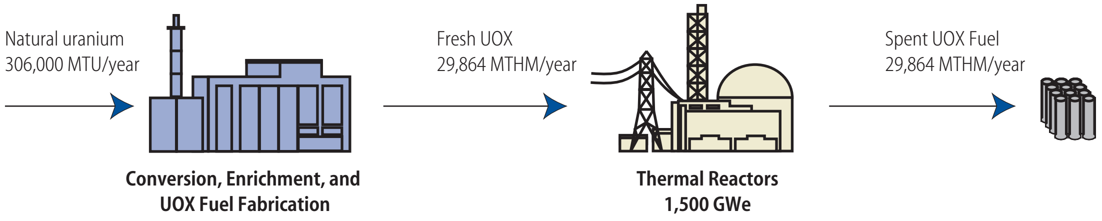
In this report, our concern is not with the description of the technical details of each fuel cycle. Rather, we stress the importance of aligning the different fuel cycle options with the global growth scenario criteria that we have specified in the last section: cost, safety, nonproliferation, and waste. This is by no means an easy task, because objective quantitative measures are not obvious, there are great uncertainties, and it is difficult to harmonize technical and institutional features. Moreover, different fuel cycles will meet the four different objectives differently, and therefore the selection of one over the other will inevitably be a matter of judgment. All too often, advocates of a particular reactor type or fuel cycle are selective in emphasizing criteria that have led them to propose a particular candidate. We believe that detailed and thorough analysis is needed to properly evaluate the many fuel cycle alternatives.

We do not believe that a new technical configuration exists that meets all the criteria we have set forth, e.g. there is not a technical ‘silver bullet’ that will satisfy each of the criteria. Accordingly, the choice of the best technical path requires a judgment balancing the characteristics of a particular fuel cycle against how well it meets the criteria we have adopted.

Our analysis separates fuel cycles into two classes: “open” and “closed.” In the open or once-through fuel cycle, the spent fuel discharged from the reactor is treated as waste. See Figure 4.1. In the closed fuel cycle today, the spent fuel discharged from the reactor is *reprocessed*, and the products are partitioned into uranium (U) and plutonium (Pu) suitable for fabrication into oxide fuel or mixed oxide fuel (MOX) for recycle back into a reactor. See Figure 4.2. The rest of the spent fuel is treated as high-level waste (HLW). In the future, closed fuel cycles could include use of a dedicated reactor that would be used to transmute selected isotopes that have been separated from spent fuel. See Figure 4.3. The dedicated reactor also may be used as a breeder to produce new fissile fuel by neutron absorption at a rate that exceeds the consumption of fissile fuel by the neutron chain reaction.[2] In such fuel cycles the waste stream will contain less actinides,[3] which will signifi-

Figure 4.1 Open Fuel Cycle: Once-Through Fuel — Projected to 2050

Current Burnup: 50 GWD/MTIHM:



High Burnup: 100 GWD/MTIHM:

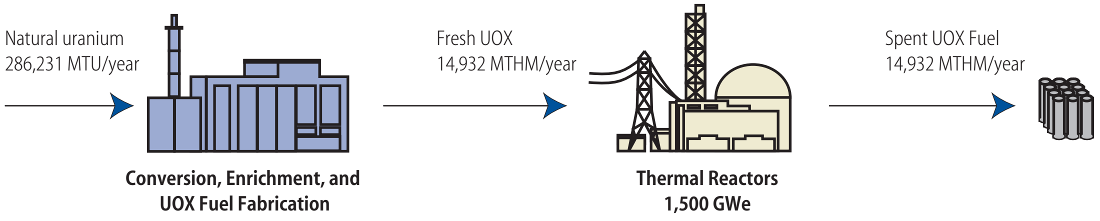


Figure 4.2 Closed Fuel Cycle: Plutonium Recycle (MOX option - one recycle) — Projected to 2050

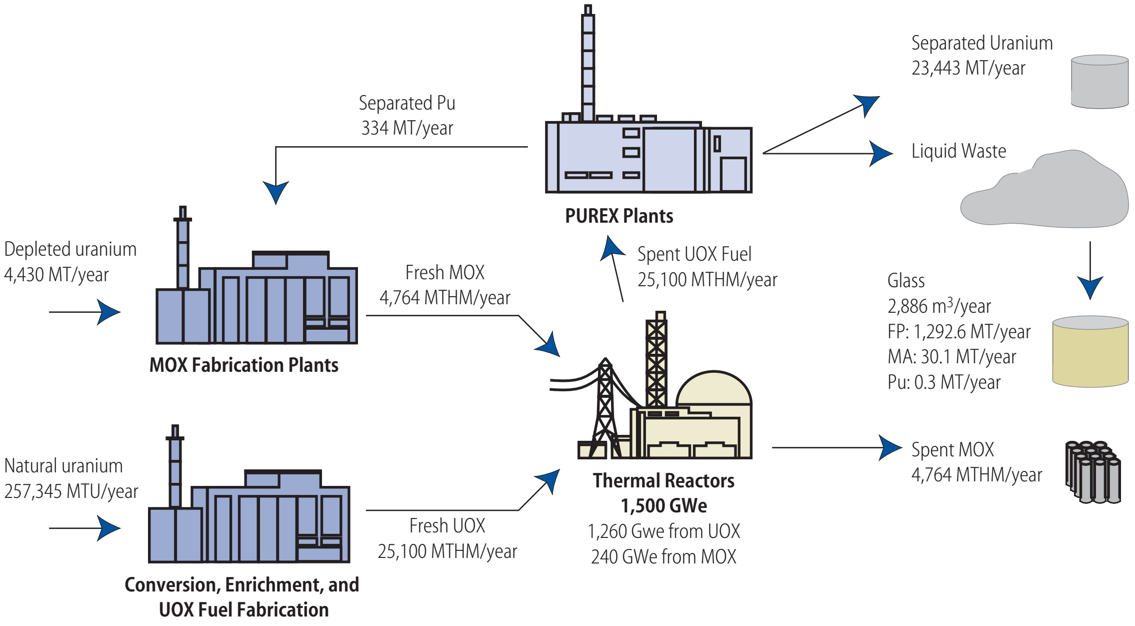
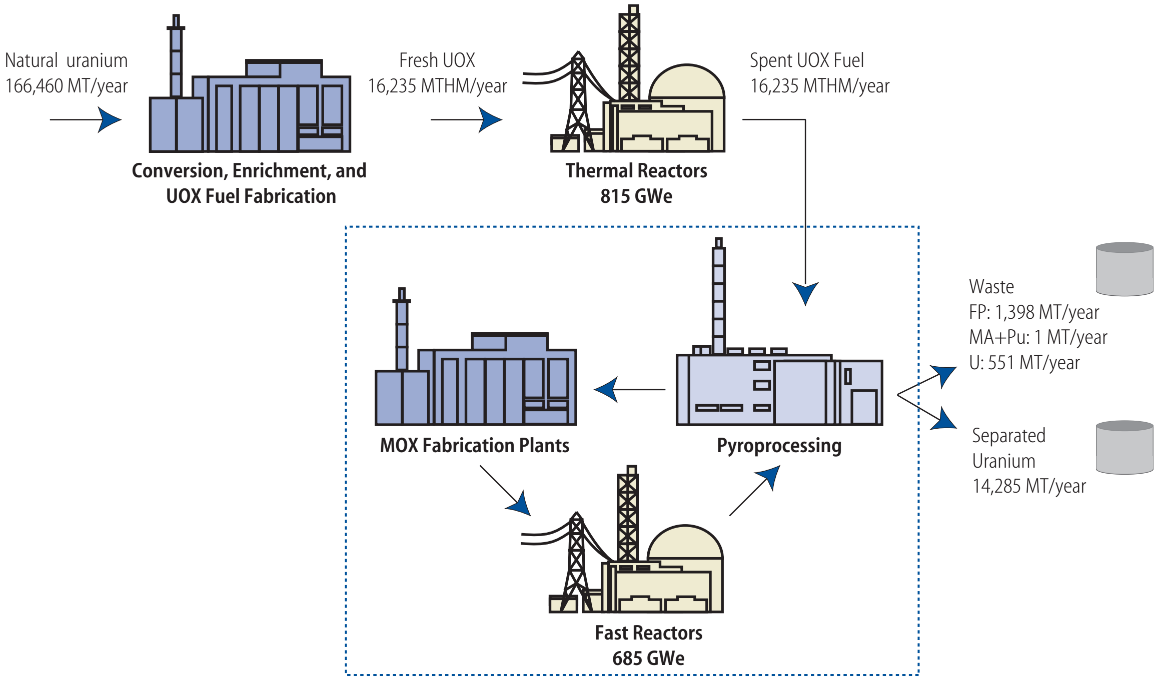


Figure 4.3 Closed Fuel Cycle: Full Actinide Recycle — Projected to 2050



cantly reduce the long-term radioactivity of the nuclear waste.[4]

In general, we expect the once-through fuel cycle to have an advantage in terms of cost and proliferation resistance (since there is no reprocessing and separation of actinides), compared to the closed cycle. Closed cycles have an advantage over the once-through cycle in terms of resource utilization (since the recycled actinides reduce the requirement for enriched uranium), which in the limit of very high ore prices would be more economical. Some argue that closed cycles also have an advantage for long-term waste disposal, since long-lived actinides can be separated from the fission products and transmuted in a reactor. Our analysis below focused on these key comparisons.

Both once-through and closed cycles can operate on U or Th fuel and can involve different reactor types, e.g., Light Water Reactors (LWRs), Heavy Water Reactors (HWRs), Supercritical water reactors (SCWRs), High Temperature and very High Temperature Gas Cooled Reactors (HTGRs), Liquid Metal and Gas Fast Reactors (LMFRs and GFRs), or Molten Salt Reactors (MSR) of various sizes. Today, almost all deployed reactors are of the LWR type. The introduction of new reactors or fuel cycles will require considerable development resources and some period of operating experience before initial deployment.

The fuel cycle characteristics of the current worldwide deployment of nuclear power (with the exception of three operating liquid metal fast breeder plants[5]) are summarized in Table 4.1. At present, plants employing the once-though enriched uranium oxide (UOX) fuel have a total capacity of about 325 GWe of electricity. In addition there are plants burning reprocessed mixed Pu and U oxide fuel (MOX) in reactors with a total capacity of about 27 GWe.[6] Current plans call for only one recycle of the fuel. Table 4.1 gives the annual material flows for the entire fleet of reactors.

The proposed mid-century deployment under the global growth scenario of this study is

Table 4.1 Fuel Cycle Characteristics of Current Plants[a]

	U FEED 10^3 MT/YR	HLW DISCHARGED YR $^{-1}$	Pu DISCHARGED MT/YR	SEPARATED Pu INVENTORY MT
UOX Plants 325 GWe	66.340	Spent UOX: 6471 MTIHM	Discharged: 89.7	—
MOX Plants 27 GWe	3.675	Spent MOX: 179 MTIHM Glass[b]: 109 m^3 Process Waste: 330 m^3	Consumed: 12.6 Discharged: 8.8	6.3[c]

a. Initial enrichment 4.5%, tails assay 0.3%, discharge burnup 50GWd/MTIHM, thermal efficiency 33%, capacity factor 90%. Values on a per GWe basis are given in appendix 4.
b. Requires reprocessing of 944 MTIHM spent UOX per year (0.6 La Hague equivalents). Borosilicate glass contains: 48.6 MT FP, 1.1 MT Pu+MA.
c. Separated Pu storage time is assumed to be 6 months. See Brogli, Krakowski, "Degree of Sustainability of Various Nuclear Fuel Cycles," Paul Scherrer Institut, August 2002.

achieved either by exclusive use of the once-through cycle with current LWRs (option one) or by plutonium recycle (where all the spent UOX but none of the spent MOX is reprocessed) with current LWRs (option two). Under both of these options, material flows increase significantly, as presented in Table 4.2.

The once-through fuel cycle is a technically credible option, assuming there is sufficient uranium ore available at reasonable cost to support a deployment of this size. Note that the single-pass[7] thermal reprocessing option uses almost as much U ore as the once-through system. Furthermore, if there is adequate ore supply at reasonable prices, then the single-pass recycle option will not be economically attractive compared to the once through option as Appendix 4.1 discusses.

As indicated in Table 4.2, the thermal recycle option does have an advantage in producing less material requiring permanent waste disposal, but this is balanced by greater transuranic (TRU)[8] waste produced during reprocessing. Furthermore, the fission product

Table 4.2 Fuel Cycle Characteristics Projected to Mid-Century

	1500 GWE FLEET PER YEAR IN 2051			
	U FEED 10^3 MT/YEAR	**HLW DISCHARGED YEAR $^{-1}$**	**Pu DISCHARGED MT/YEAR**	**SEPARATED Pu INVENTORY MT**
Scenario 1 Once-through 1500 GWe	306	Spent UOX: 29 864 MTIHM	Discharged: 397	—
Scenario 2 Thermal Recycle[d] UOX Plants: 780 GWe MOX Plants: 720 GWe	257	Glass a: 2886 m^3 Process Waste: 8785 m^3 Spent MOX: 4764 MTIHM	Discharged: 233	167[e]
	FLEET CUMULATIVE, FROM 352GWE IN 2002 TO 1500 GWE IN 2051			
	U FEED 10^6 MT	**HLW DISCHARGED**	**Pu DISCHARGED 10^3 MT**	—
Scenario 1 Once-through 1500 GWe	9.45	Spent UOX: $922 \cdot 10^3$ MTIHM (13.2 YMEs[c])	Discharged: 12.0	—
Scenario 2 Thermal Recycle[d] UOX Plants: 780 GWe MOX Plants: 720 GWe	8.18	Spent UOX: $147 \cdot 10^3$ MTIHM Spent MOX: $124 \cdot 10^3$ MTIHM Glass[b]: $75 \cdot 103$ m^3 Process Waste: $228 \cdot 103$ m^3	Discharged: 8.0	—

a. Requires reprocessing of 26 335 MTIHM spent UOX per year (14 La Hague equivalents). Borosilicate glass contains: 1292.6 MT FP, 30 MT MA, 0.3 MT Pu.
b. Requires reprocessing of $651 \cdot 10^3$ MTIHM spent UOX. Borosilicate glass contains: $33.5 \cdot 10^3$ MT FP, 781 MT MA, 8.7 MT Pu.
c. YME : Yucca Mountain Equivalent (70 000 MTIHM).
d. MOX Plants have 2/3 of the core loaded with UOX and 1/3 loaded with MOX. Hence, 540 GWe is generated from UOX, and 240 GWe is generated from MOX.
e. Separated Pu storage time is assumed to be 6 months. See Brogli, Krakowski, “Degree of Sustainability of Various Nuclear Fuel Cycles,” Paul Scherrer Institut, August 2002.

Table 4.3 Global Growth Scenario — Fuel Cycle Parameter comparison. Annual Amounts for 1500 GWe Deployment[a] *See Appendix 4 for fuel cycle calculations.*

	OPTION 1A ONCE THROUGH LOW BURN UP	OPTION 1B ONCE THROUGH HIGH BURN UP	OPTION 3 LWR + FAST REACTOR[b]	
			LWR	Fast reactor
Capacity, GWe	1,500	1,500	815	685
Enrichment, %	4.5	8.2	4.5	25
Burn up, GWd/MTIHM	50	100	50	120
Uranium ore				
per year, 10^3 MT/yr	306	286	166	
cumulative, 10^6 MT	9.45	8.76	5.96	
Spent or repr. Fuel				
per year, 10^3 MTIHM/yr	29.9	14.9	Repr.: 20.9 (12.3 LHE[c])	
cumulative, 10^3 MTIHM	922 (13.7 YME)	516 (7.4 YME)	Spent : 4.1 YMEs	
HLW, MT/yr	Not applicable	Not applicable	FP: 1398; MA+Pu: 1.0	
Pu, MT/yr	397	294	0.7 (repr. losses)	
Waste decay heat[d]				
W/GWeY (100 yrs)	$1.1 \cdot 10^4$	$1.1 \cdot 10^4$	$2.8 \cdot 10^3$	
Waste ingestion hazard				
m^3/GWeY (1,000 yrs)	$6.9 \cdot 10^{11}$	$5.3 \cdot 10^{11}$	$2.2 \cdot 10^7$	

a. Thermal efficiency 33% for LWRs and 40% for FRs, capacity factor 90%, enrichment tails assay 0.3%. Capacity is assumed to increase linearly. Fast reactors start deployment in 15 years.

b. Intended as generic fast reactor; data from ANL IFR.

c. LHE means La Hague equivalent (1,700 MTHM/year)

d. The decay heat and radiotoxicity are computed from and MCODE/ORIGEN run and expressed on a per GWe-y basis to establish a fair comparison between the various fuel cycles. The decay heat and radiotoxicity per unit mass can be obtained by dividing by the mass of spent fuel discharged per GWe-y. The spent fuel discharge for option 1A is 22.1 MTIHM/y, giving a decay heat at 100 years of 5.0·102 W/MTIHM and a radiotoxicity at 1000 years of 3.1·1010 m3/MTIHM, as shown in Figures 7.2 and 7.3.

inventory is essentially the same. Most important, the thermal recycle case has a large amount of Pu separated each year.[9] The separated plutonium inventory required for option two is 167 metric tons. A nuclear weapon of significant yield can comfortably be made with less than 10kg of Pu, so this amount represents the potential for thousands of nuclear weapons. Thus, the once-through thermal recycle scenario will not be a reasonable mid-century state, so long as U ore is available at reasonable prices. If ore prices were to become very high, the one-pass thermal recycle option would potentially be attractive, but under those conditions, a fuel cycle that includes reactors that transmute actinides must then be considered (option 3). Single-pass thermal recycle is not an attractive approach for nuclear energy for the next half century.

In option 3 we consider a *fully closed fuel cycle*. This fuel cycle is exactly balanced so the number of fast reactors deployed is sufficient to burn all the actinides produced in once through thermal reactors. Only the fast reactor fuel is reprocessed, presumably in a developed country and a 'secure' energy park; the thermal reactors operating on a once-through cycle, can be located anywhere. This configuration has proliferation advantage over the situation considered in option two, as discussed in Chapter 8. *It is important to note that this balanced closed fuel cycle is entirely different from breeder fast reactor fuel cycles where net plutonium produced in fast reactors is made into MOX fuel to be burned in thermal reactors.* In the closed fuel cycle we considered, the fast reactor burns plutonium and actinides created in the thermal reactor.

In Table 4.3, we describe three illustrative deployments of 1500 reactors each with rated capacity of 1000 MWe, in order to give a more concrete impression of what the global growth scenario might look like. Option one is expanded and option two is replaced by a fully closed fuel cycle. The three options are:

- ☐ *Base line*. 1000 MWe LWRs operating on a oncethrough fuel cycle with today's typical characteristics. (Option 1A);
- ☐ *Advanced once-through* LWRs , perhaps with some smaller, modular HTGR nuclear systems, with higher fuel burnup characteristics that better meet the four objectives. (Option 1B);
- ☐ *Fast reactors* deployed in developed countries with a balanced closed fuel cycle. Reprocessing, fuel fabrication, and fast reactor burners are co-located in secure nuclear energy "parks." In the developing world, the deployment is largely once-through LWR fuel cycle (Option 3).

AVAILABILITY OF URANIUM RESOURCES

How long will the uranium ore resource base be sufficient to support large-scale deployment of nuclear power without reprocessing and/or breeding?[10] Present data suggests the required resource base will be available at an affordable cost for a very long time. Estimates of both known and undiscovered uranium resources at various recovery costs are given in the NEA/IAEA "Red Book"[11]. For example, according to the latest edition of the Red Book, known resources[12] recoverable at costs < \$80/kgU and < \$130/kgU are approximately 3 and 4 million tonnes of uranium, respectively. However, the amount of known resources depends on the intensity of the exploration effort, mining costs, and the price of uranium. Thus, any predictions of the future availability of uranium that are based on current mining costs, prices and geological knowledge are likely to be extremely conservative.

For example, according to the Australian Uranium Information Center, a doubling of the uranium price from its current value of about \$30/kgU could be expected to create about a ten-fold increase in known resources recoverable at costs < \$80/kgU[13] i.e., from about 3 to 30 million tonnes. By comparison, a fleet of 1500 1000 MWe reactors operating for 50 years requires about 15 million tonnes of uranium (306,000 MTU/yr as indicated in Table 4.2), using conventional assumptions about burn-up and enrichment.

Moreover, there are good reasons to believe that even as demand increases the price of uranium will remain relatively low: the history of all extractive metal industries, e.g., copper, indicates that increasing demand stimulates the development of new mining technology that greatly decreases the cost of recovering additional ore. Finally, since the cost of uranium represents only a small fraction of the busbar cost of nuclear electricity, even large increases in the former — as may be required to recover the very large quantities of uranium contained at low concentrations in both terrestrial deposits and seawater — may not substantially increase the latter.[14] In sum, we conclude that resource utilization is not a pressing reason for proceeding to reprocessing and breeding for many years to come.

NOTES

1. See, for example, OECD Nuclear Energy Agency, Trends in the Nuclear Fuel Cycle ISBN 92-64-19664-1 (2001) and Nuclear Science Committee "Summary of the workshop on advanced reactors with innovative fuel," October 1998, NEA/NSC/DOC(99)2.
2. Several nations have explored breeder reactors, notably the U.S., France, Russia, Japan, and India.
3. Minor actinides are Americium (Am),Neptunium (Np), and Curium (Cm).
4. There are still other options, such as using an accelerator to produce neutrons in a sub-critical assembly.
5. The three surviving developmental breeder reactors are Phenix in France, Monju in Japan, and BN600 in Russia.
6. The MOX fueled plants are currently operating with only about a third of their core loaded as MOX fuel; the balance is UOX fuel. Hence only about 9 GWe are being generated in these reactors from the MOX fuel
7. Single pass recycle means that a discharged fuel batch is reprocessed once only.
8. TRU here refers to the U.S. definition: low-level waste contaminated with transuranic elements.
9. Due to process holding time, the actual amount of separated Pu inventory could be several or more years' worth of separations.
10. For additional details, see Appendix 5-E and Marvin Miller, *Uranium resources and the future of nuclear power,* Lecture notes, MIT, Spring 2001; for copies contact marvmiller@mit.edu.
11. Uranium resources, production, and demand ("The Red Book"), OECD Nuclear Energy Agency and International Atomic Energy Agency, 2001.
12. Such resources are also known as measured resources and reserves.
13. Uranium Information Center, "Nuclear Electricity", 6th edition, Chapter 3 (2000). Available on the web at http:www.uic.com.au/ne3.htm.
14. For example, recent research in Japan indicates that uranium in seawater — present in concentration of 3.3 ppb — might be recovered at costs in the range of $300–$500/kg.

Chapter 5 — Nuclear Power Economics

Investments in commercial nuclear generating facilities will only be forthcoming if investors expect the cost of producing electricity using nuclear power will be lower than the risk-adjusted costs associated with alternative electric generation technologies. Since nuclear power plants have relatively high capital costs and very low marginal operating costs, nuclear energy will compete with alternative electricity generation sources for “baseload” (high load factor) operation. We recognize that over the next 50 years some significant but uncertain fraction of incremental electricity supplies will come from renewable energy sources (e.g. wind) either because these sources are less costly than alternatives or because government policies (e.g. production tax credits, high mandated purchase prices, and renewable energy portfolio standards) or consumer choice favor renewable energy investments. Despite the efforts to promote renewable energy options, however, it is likely that a large fraction of the incremental and replacement investments in electric generating capacity needed to balance supply and demand over the next 50 years will, in the absence of a nuclear generation option, rely on fossil-fuels — primarily natural gas or coal. This is particularly likely in developing countries experiencing rapid growth in income and electricity consumption. Accordingly, we focus on the costs of nuclear power compared to these fossil fuel generating alternatives in base-load applications.

Any analysis of the costs of nuclear power must take into account a number of important considerations. First, all of the nuclear power plants operating today were developed by state-owned or regulated investor-owned vertically-integrated utility monopolies.[1] Many developed countries and an increasing number of developing countries are in the process of moving away from an electric industry structure built upon vertically integrated regulated monopolies to an industry structure that relies primarily on competitive generation power plant investors. We assume that in the future nuclear power will have to compete with alternative generating technologies in competitive wholesale markets — as merchant plants.[2] These changes in the structure of the electric power sector have important implications for investment in generating capacity. Under traditional industry and regulatory arrangements, many of the risks associated with construction costs, operating performance, fuel price changes, and other factors were borne by consumers rather than suppliers.[3] The insulation of investors from many of these risks necessarily had significant effects on the cost of capital they used to evaluate alternative generation options and on whether and how they took extreme contingencies into account. Specifically, the process reduced the cost of capital and led investors to give less weight to regulatory (e.g. construction and operating licenses) and construction cost uncertainty, operating performance uncertainties and uncertainties associated with future oil, gas and coal prices than if they had to bear these cost and performance risks.

In a competitive generation market it is investors rather than consumers who must bear the risk of uncertainties associated with obtaining construction and operating permits, construction costs and operating performance. While some of the risks associated with uncertainties about the future market value of electricity can be shifted to electricity marketers and consumers through forward contracts, some market risk and all construction cost, operating cost and performance risks will continue to be held by power plant investors.[4] Thus, the shift to a competitive electricity market regime necessarily leads investors to favor less capital-intensive and shorter construction lead-time investments, other things equal.[5] It may also lead investors to favor investments that have a natural "hedge" against market price volatility, other things equal.[6]

Second, the construction costs of nuclear plants completed during the 1980s and early 1990s in the United States and in most of Europe were very high — and much higher than predicted today by the few utilities now building nuclear plants and by the nuclear industry generally. The reasons for the poor historical construction cost experience are not well understood and have not been studied carefully. The realized historical construction costs reflected a combination of regulatory delays, redesign requirements, construction management and quality control problems. Moreover, construction on few new nuclear power plants has been started and completed anywhere in the world in the last decade. The information available about the true costs of building nuclear plants in recent years is also limited. Accordingly, the future construction costs of building a large fleet of nuclear power plants is necessarily uncertain, though the specter of high construction costs has been a major factor leading to very little credible commercial interest in investments in new nuclear plants. Finally, while average U.S. nuclear plant availability has increased steadily during the 1990s to a high of 90% in 2001, many nuclear plants struggled with low availabilities for many years and the life-cycle availability of the fleet of nuclear plants (especially taking account of plants that were closed early) is much less than 90%.[7] In addition, the average operation and maintenance costs of U.S. nuclear plants (including fuel) were over $20/MWh during the 1990s (though average O&M costs had fallen to about $18/MWe-hr and the lowest cost quartile of plants to about $13/MWe-hr by 2001)[8], rather than the $10/MWe-hr often assumed in many paper engineering cost studies.

Third, even if an investment in nuclear power looked attractive on a spreadsheet, investors must confront the regulatory and political challenges associated with obtaining a license to build and operate a plant on a specific site. In the past, disputes about licensing, local opposition, cooling water source and discharge requirements, etc., have delayed construction and completion of nuclear plants. Many planned plants, some of which had incurred considerable development costs, were cancelled. Delays and "dry-hole" costs are especially burdensome for investors in a competitive electricity market.

With these considerations in mind, we now proceed to examine the relative costs of new nuclear power plants, pulverized coal plants, and combined-cycle gas turbine (CCGT) plants in base-load operations in the United States.[9] The analysis is not designed to produce precise estimates, but rather a "reasonable" range of estimates under a number of different assumptions reflecting uncertainties about future construction and operating costs. Similar analysis for Europe and especially Japan and Korea would be somewhat more favorable to nuclear, since gas and coal costs are typically higher than in the United States.

We start with a "base case" that examines the levelized *real* life-cycle costs of nuclear, coal, and CCGT generating technology using assumptions that we believe commercial investors would be expected to use today to evaluate the costs of the alternative generation options. The levelized cost is the constant real wholesale price of electricity that meets a private investor's financing cost, debt repayment, income tax, and associated cash flow constraints.

The base case assumes that non-fuel O&M costs can be reduced by about 25% compared to the recent operating cost experience of the average nuclear plant operating in the U.S. in the last few years. This puts the total O&M costs (including fuel) at about 15 mills/kWe-hr. We include this reduction in O&M costs in the base case because we expect that operators of new nuclear plants in a competitive wholesale electricity market environment will have to demonstrate better than average performance to investors. The 15 mill O&M cost value is consistent with the performance of existing plants that fall in the second lowest cost quartile of operating nuclear plants.[10] (The assumptions underlying the base case are listed in Table 5.3 and illustrative cash flows produced by our financial model are provided in Appendix 5.)

We then examine how the real levelized cost of nuclear generated electricity changes as we allow for *additional* cost improvements. First, we assume that construction costs can be reduced by 25% from the base case levels to more closely match optimistic but plausible forecasts. Second, we examine how life-cycle costs are further reduced by a one-year reduction in construction time. Third, we examine the effects of reducing financing costs to a level comparable to what we assume for gas and coal generating units as a consequence of, for example, reducing regulatory risks and commercial risks associated with uncertainties about construction and operating costs that presently burden nuclear compared to fossil-fueled alternatives. This reduction in financial risk might result from an effective commercial demonstration program of the type that we discuss further in Part II. Finally, we examine how the relative costs of coal and CCGT generation are affected by placing a "price" on carbon emissions, through carbon taxes, the introduction of a carbon emissions cap and trade program, or equivalent mechanism to price carbon emissions to internalize their social costs into investment decisions in a way that treats all supply options on an equivalent basis. We consider carbon prices in a range that brackets current estimates of the costs of carbon sequestration (capture, transport and storage). The latter analysis provides a framework for assessing the option value of nuclear power if and when the United States adopts a program to stabilize and then reduce carbon emissions.

The levelized cost of electric generating plants has typically been calculated under the assumption that their regulated utility owners recover their costs using traditional regulated utility cost of service cost recovery rules. Investments were recovered over a 40 year period and debt and equity were repaid in equal proportions over this lengthy period at the utility's cost of capital, which reflected the risk reducing effects of regulation. Moreover, the calculations typically provided levelized *nominal* cost values rather than levelized *real* cost values, obscuring the effects of inflation and making capital intensive technologies look more costly relative to alternatives than they really were.

We do not believe that these traditional levelized cost models based on regulated utility cost recovery principles provide a good description of how merchant plants will be financed in the future by private investors. Accordingly, we have developed and utilized an alternative model that provides flexibility to specify more realistic debt repayment obligations and associated cash flow constraints, as well as the costs of debt and equity and income tax obligations that a private firm would assign to individual projects with specific risk attributes, while accounting for corporate income taxes, tax depreciation and the tax shield on interest payments. We refer to this as the Merchant Cash Flow model. We have relied primarily on simulation results using this model under assumptions of both a 25-year and 40-year capital recovery period and 85% and 75% lifetime capacity factors.

BASE CASE

The base case reflects reasonable estimates of the current perceived costs of building and operating the three generating alternatives in 2002 U.S. dollars. The overnight capital cost for nuclear in the base case is $2000/kWe. As discussed in Appendix 5, this value is consistent with estimates made by the U.S. Energy

Information Administration (EIA), estimates reported by other countries to the OECD, and recent nuclear plant construction experience abroad. We have not relied on construction cost data for U.S. plants completed in the late 1980s and early 1990s; if we had, the average overnight construction cost in 2002 U.S. dollars would have been much higher. We are aware that some vendors and some potential investors in new nuclear plants believe that they can achieve much lower construction costs. We consider significant construction cost reductions in our discussion of improvements in nuclear costs.[11]

As previously discussed, our base case assumes that O&M costs are 15 mills/kWe-hr, which is lower than the recent experience for the average nuclear plant and is consistent with the recent performance of plants in the second lowest cost quartile of operating nuclear plants in the U.S. The O&M costs of plants in the lowest cost quartile (best performers) are about 13 mills/kWe-hr. We consider this to represent the potential for further cost improvements for a fleet of new nuclear plants but we do not believe that investors will assume that all plants will achieve the O&M cost levels of the best performers.

The construction costs assumed for CCGT and coal plants are in line with experience and EIA estimates. The construction cost of the coal plant is assumed to reflect NOx and SO_2 controls as required to meet current New Source Performance Standards. There are four cases presented for the CCGT plants: (1) a low gas price case that starts with gas prices at \$3.50/MMBtu which rise at a real rate of 0.5% over 40 years (real levelized cost of \$3.77/MMbtu over 40 years); (2) a moderate gas price case with gas prices starting at \$3.50/MMBtu as well, but rising at a real rate of 1.5% per year over 40 years (real levelized cost of \$4.42 over 40 years); (3) high gas price case that starts at \$4.50/MMbtu and rises at a real rate of 2.5% per year (real levelized cost of \$6.72/Mmbtu over 40 years). (4) The fourth CCGT case reflects high gas prices and an advanced CCGT design with a (roughly) 10% improvement in its heat rate. The base case results for 25 and 40-year economic lives and 85% capacity factor are reported in Table 5.1 and the equivalent results for a 75% lifetime capacity factor are reported in Table 5.2. The assumptions for the cases are given in Table 5.3. The discussion that follows is based on the 85% capacity factor simulations since the basic results don't change very much when we assume the lower capacity factor.

The base case results suggest that nuclear power is much more costly than the coal and gas alternatives even in the high gas price cases. In the low gas price case, CCGT is cheaper than coal. In the moderate gas price case, total life-cycle coal and gas costs are quite close together, though we should recognize that there are regions of the country with below average coal costs where coal would be less costly than gas and vice versa. Under the high gas price assumption, coal beats gas by a significant amount. (We have not tried to account for the relative difficulties of siting coal and gas plants.) We discuss potential future carbon emissions regulations separately below.

This suggests that high natural gas prices will eventually lead investors to switch to coal rather than to nuclear under the base case assumptions as nuclear appears to be so much more costly than coal and U.S. coal supplies are very elastic in the long run so that significant increases in coal demand will not lead to significant increases in long term coal prices. In countries with less favorable access to coal, the gap would be smaller, but 2.5 cents/kWe-hr is too large a gap for nuclear to beat coal in many areas of the world under the base case assumptions (absent additional restrictions on emissions of carbon dioxide from coal plants which we examine separately below).

The bottom line is that with current expectations about nuclear power plant construction costs, operating cost and regulatory uncertainties, it is extremely unlikely that nuclear power will be the technology of choice for merchant plant investors in regions where suppliers have access to natural gas or coal resources. It is just too expensive. In countries that rely on state owned enterprises that are willing and able to shift cost risks to consumers to reduce the cost of capital, or to subsidize financing costs directly, and which face high gas and coal costs, it is possible that nuclear power could be perceived to be an economical choice.[12]

IMPROVEMENTS IN NUCLEAR COSTS

We next examine how the cost of electricity generated by nuclear power plants would change, if effective actions can be taken to reduce nuclear electric generation costs in several different ways. First, we assume that construction costs can be reduced by 25%. This brings the construction costs of a nuclear plant to a level more in line with what the nuclear industry believes is feasible in the medium term under the right conditions.[13] While this reduces the levelized cost of nuclear electricity considerably, it is still not competitive with gas or coal for any of the base cases. Reducing construction time from 5 years to 4 years reduces the levelized cost further, but not to a level that would make it competitive with fossil fuels. However, if regulatory, construction and operating cost uncertainties could be resolved, and the nuclear plant could be financed under the same terms and conditions (cost of capital) as a coal or gas plant, then the costs of nuclear power become very competitive with the costs of CCGTs in a high gas price world and only slightly more costly than pulverized coal plants, assuming that comparable improvements in the costs of building coal plants are not also achieved. If nuclear plant operators could reduce O&M costs by another 2 mills to 13 mills/kWe-hr, consistent with the best performers in the industry, nuclear's total cost would match the cost of coal and the cost of CCGT in the moderate and high gas price cases. However, nuclear does not have a meaningful economic advantage over coal.

These results suggest that with significant improvements in the costs of building, operating, and financing nuclear power plants, and continued excellent operating performance (85% capacity factor), nuclear power could be quite competitive with natural gas if gas prices turn out to be higher than what most analysts now appear to believe and would be only slightly more costly than coal within the range of assumptions identified.[14]

The cost improvements we project are plausible but unproven. It should be emphasized, that the cost improvements required to make nuclear power competitive with coal are significant: 25% reduction in construction costs; greater than a 25% reduction in non-fuel O&M costs compared to recent historical experience (reflected in the base case), reducing the construction time from 5 years (already optimistic) to 4 years, and achieving an investment environment in which nuclear power plants can be financed under the same terms and conditions as can coal plants. Moreover, under what we consider to be optimistic, but plausible assumptions, nuclear is never less costly than coal.

CARBON "TAXES"

From a societal cost perspective, all external social costs of electricity generation should be reflected in the price. Here we consider the cost of CO_2 emissions and not other externalities; for example we ignore the costs of other air pollutants from fossil fuel combustion and nuclear proliferation and waste issues (except for including the costs of new coal plants to meet new source performance standards). Nuclear looks more attractive when the cost of CO_2 emissions is taken into account. Unlike gas and coal-fired plants, nuclear plants produce no carbon dioxide during operation and do not contribute to global climate change. Accordingly, it is natural to explore what the comparative social cost of nuclear power would be, if carbon emissions were "priced" to reflect the marginal cost of achieving global carbon emissions stabilization and reduction targets.[15] Future United States policies regarding carbon emissions are uncertain at the present time.

Table 5.1 Costs of Electric Generation Alternatives
Real Levelized Cents/kWe-hr (85% capacity factor)

Base Case	25-YEAR	40-YEAR
Nuclear	7.0	6.7
Coal	4.4	4.2
Gas (low)	3.8	3.8
Gas (moderate)	4.1	4.1
Gas (high)	5.3	5.6
Gas (high) Advanced	4.9	5.1
Reduce Nuclear Costs Cases		
Reduce construction costs (25%).	5.8	5.5
Reduce construction time by 12 months	5.6	5.3
Reduce cost of capital to be equivalent to coal and gas	4.7	4.4

Carbon Tax Cases (25/40 year)

	$50/tC	$100/tC	$200/tC
Coal	5.6/5.4	6.8/6.6	9.2/9.0
Gas (low)	4.3/4.3	4.9/4.8	5.9/5.9
Gas (moderate)	4.6/4.7	5.1/5.2	6.2/6.2
Gas (high)	5.8/6.1	6.4/6.7	7.4/7.7
Gas (high) advanced	5.3/5.6	5.8/6.0	6.7/7.0

Table 5.2 Costs of Electric Generation Alternatives
Real Levelized Cents/kWe-hr (75% capacity factor)

Base Case	25-YEAR	40-YEAR
Nuclear	7.9	7.5
Coal	4.8	4.6
Gas (low)	4.0	3.9
Gas (moderate)	4.2	4.3
Gas (high)	5.5	5.7
Gas (high) advanced	5.0	5.2
Reduce Nuclear Costs Cases		
Reduce construction costs (25%)	6.5	6.2
Reduce construction time by 12 months	6.2	6.0
Reduce cost of capital to be equivalent to coal and gas	5.2	4.9

Carbon Tax Cases (25/40 year)

	$50/tC	$100/tC	$200/tC
Coal	6.0/5.8	7.2/7.0	9.6/9.4
Gas (low)	4.5/4.4	5.0/5.0	6.0/6.0
Gas (moderate)	4.7/4.8	5.3/5.3	6.3/6.4
Gas (high)	6.0/6.3	6.5/6.8	7.5/7.8
Gas (high) advanced	5.5/5.7	5.9/6.2	6.8/7.1

By examining the relative economics of nuclear power under different assumptions about future social valuations for reducing carbon emissions, we can get a feeling for the option value of nuclear generation in a world with carbon emissions restrictions of various severities.

To examine this question we have recalculated the costs of the fossil-fueled generation alternatives to reflect a carbon tax of $50/tC, $100/tC, and $200/tC. The lower value is consistent with an EPA estimate of the cost of reducing U.S. CO_2 emissions by about 1 billion metric tons per year.[16] The $100/tC and $200/tC values bracket the range of values that appear in the literature regarding the costs of carbon sequestration, recognizing that there is enormous uncertainty about the costs of deploying CO_2 capture, transport, and storage on a large scale. These hypothetical taxes should be thought of as a range of “backstop” marginal costs for reducing carbon emissions to meet aggressive global emissions goals. These results are reported in Table 5.1 and 5.2, as well.

With carbon taxes in the $50/tC range, nuclear is not economical under the base case assumptions. If nuclear costs can be reduced to reflect all of the cost-reduction specifications discussed earlier, nuclear would be less costly than coal and less costly than gas in the high gas price cases. It is roughly competitive with gas in the low and moderate price gas cases. With carbon taxes in the $100/tC to $200/tC range, nuclear power would be an economical base load option compared to coal under the base case assumptions, but would still be more costly than gas except in the high gas price case. However, nuclear would be significantly less costly than all of the alternatives with carbon prices at this level, if all of the cost reduction specifications discussed earlier could be achieved.

The last conclusion ignores one important consideration. With carbon taxes at these high levels, it could become economical to deploy a generating technology involving the gasification of coal, its combustion in a CCGT (IGCC), and the sequestration of carbon dioxide produced in the process. The potential cost savings from this technology compared to conventional pulverized coal plants arises from (a) the use of relatively inexpensive coal to produce syngas (mostly CO and H_2) (b) the higher thermal efficiency of CCGT, and more economical capture of CO_2. Depending on the economics of this technology, coal could play a larger competitive role in a world with high carbon taxes than might be suggested by Tables 5.1 and 5.2. We observe as well, that from an environmental perspective, the world looks very different if there are abundant supplies of cheap natural gas, than if natural gas supplies are scarcer and significantly more expensive than many recent projections imply.

Table 5.3 Base Case Assumptions

Nuclear	
Overnight cost:	$2000/kWe
O&M cost:	1.5 cents/kWh (includes fuel)
O&M real escalation rate:	1.0%/year
Construction period:	5 years
Capacity factor:	85%/75%
Financing:	
Equity: 15% nominal net of income taxes	
Debt: 8% nominal	
Inflation: 3%	
Income Tax rate (applied after expenses, interest and tax depreciation): 38%	
Equity: 50%	
Debt: 50%	
Project economic life:	40 years/25 years
Coal	
Overnight cost:	$1300/kWe
Fuel Cost:	$1.20/MMbtu
Real fuel cost escalation:	0.5% per year
Heat rate (bus bar):	9300 BTU/klWh
Construction period:	4 years
Capacity factor:	85%/75%
Financing:	
Equity: 12% nominal net of income taxes	
Debt: 8% nominal	
Inflation: 3%	
Income Tax rate (applied after expenses, interest and tax depreciation): 38%	
Equity: 40%	
Debt: 60%	
Project economic life:	40 years/25 years
Gas CCGT	
Overnight cost:	$500/kWe
Initial fuel cost:	
Low: $3.50/MMbtu ($3.77/MMbtu real levelized over 40 years)	
Moderate: $3.50/MMbtu ($4.42/MMbtu real levelized over 40 years)	
High: $4.50/MMbtu ($6.72/MMbtu real levelized over 40 years)	
Real fuel cost escalation:	
Low: 0.5% per year	
Moderate: 1.5% per year	
High: 2.5% per year	
Heat rate:	7200 BTU/kWh
Advanced:	6400 BTU/kWh
Construction period:	2 years
Capacity factor:	85%/75%
Financing:	
Equity: 12% nominal net of income taxes	
Debt: 8% nominal	
Inflation: 3%	
Income tax rate (applied after expenses, interest and tax depreciation): 38%	
Equity: 40%	
Debt: 60%	
Project economic life:	40 years/25 years

INTERNATIONAL PERSPECTIVE ON COST OF ELECTRICITY

The methodology followed above is pertinent to an electricity generation market that is unregulated, a situation that the United States is moving toward, as are several other countries. An additional advantage to describing deregulated market situations is that the methodology properly focuses on the true economic cost of electricity generating alternatives. There are however many nations that do not enjoy an unregulated generating market and are unlikely to adopt deregulation for some time to come. In many of these countries electricity generation is run directly or indirectly by the government and significant subsidies are provided to generating facilities. The electricity "cost" in these countries is not transparent and leads to a different political attitude toward investment decisions because consumers enjoy subsidized prices. The result is a misallocation of resources and over the long-run one can expect that political and economic forces will call for change. These non-market situations are encountered in Europe, e.g. Electricite de France, although there is a strong move to deregulation in the EU and in developing countries that frequently have state run power companies. Importantly, the costs of advanced fuel cycle technologies such as PUREX reprocessing and MOX fabrication are heavily subsidized reflecting political rather than economic decision making.

COST OF ADVANCED FUEL CYCLES.

We have not undertaken as complete analysis for the costs of advanced fuel cycles as we have for the open fuel cycle. We have however examined in some detail the cost of the closed fuel cycle with single pass PUREX/MOX relative to the open cycle. This analysis is reported in the Appendix 5.D.

The fuel cycle cost model presented in Appendix 5.D shows that the closed cycle PUREX/MOX option fuel costs are roughly 4 times greater than for the open cycle, using estimated costs under U.S. conditions. The closed cycle can be shown to be competitive with the once-through option only if the price of uranium is high and if optimistic assumptions are made regarding the cost of reprocessing, MOX fabrication, and high level waste disposal. As explained in Appendix 5.D, the effect of the increased MOX fuel cycle cost on the cost of electricity depends upon the percentage of MOX fuel in the entire fleet if fuel costs are blended.

The case is often advanced that disposing of reprocessed high level waste will be less expensive than disposing of spent fuel directly. But there can be little confidence today in any estimate of such cost savings, especially if disposal of non-high-level waste contaminated with significant quantities of long-lived transuranic radionuclides (TRU waste) associated with recycle facilities and operations is taken into account. Furthermore, our cost model shows that even if the cost of disposing of reprocessed high-level waste were zero, the basic conclusion that reprocessing is uneconomic would not change.

It should be noted that the cost increment associated with reprocessing and thermal recycle is small relative to the total cost of nuclear electricity generation. In addition, the uncertainty in any estimate of fuel cycle costs is extremely large.

NOTES

1. Though in the United States and the United Kingdom some nuclear plants were subsequently sold or transferred to merchant generating companies.
2. Merchant plants sell their output under short, medium and longer term supply contracts negotiated competitively with distribution companies, wholesale and retail marketers. The power plant developers take on permitting, development, construction cost and operating performance risks but may transfer some or all risks associated with market price volatility to buyers (for a price) through the terms of their contracts.
3. It is often assumed that regulated monopolies were subject to "cost-plus" regulation which insulated utilities from all of these risks. This is an extreme and inaccurate characterization of the regulatory process, at least in the United States. (P.L. Joskow and R. Schmalensee, "Incentive Regulation for Electric Utilities," *Yale Journal on Regulation*, 1986; P.L. Joskow, "Deregulation and Regulatory Reform in the U.S. Electric Power Sector," in *Deregulation of Network Industries: The Next Steps* (S. Peltzman and Clifford Winston, eds.), Brookings Press, 2000). Several U.S. utilities were faced with significant cost disallowances associated with nuclear power plants they completed or abandoned, a result inconsistent with pure cost-plus regulation. Nevertheless, it is clear that a large fraction of these cost and market risks were shifted to consumers from investors when the industry was governed by regulated monopolies.
4. The current state of electricity restructuring and competition in the United States and Europe has made it difficult for suppliers to obtain forward contracts for the power they produce. We believe that this chaotic situation is unsustainable and that a mature competitive power market will make it possible for power suppliers to enter into forward contracts with intermediaries. However, these contracts will not generally be like the 30-year contracts that emerged under regulation which obligated wholesale purchasers (e.g. municipal utilities) to pay for all of the costs of a power plant in return for any power it happened to produce. In a competitive market the contracts will be for specified delivery obligations at a specified price (or price formula), will tend to be much shorter (e.g. 5-year contract portfolios), and will place cost and operating performance risk on the generator not on the customer.

5. Oversimplifying, these effects can be thought of as an increase in the cost of capital faced by investors.

6. For example, in areas of the United States where the wholesale market tends to clear with conventional gas or oil-fired power plants on the margin, spot market clearing prices will move up and down with the price of natural gas and oil. A combined cycle gas turbine (CCGT) that also burns natural gas, but with a heat rate 35% lower on average than those of the marginal gas plants that clear the market (e.g. 11,000 BTU/kWh), will always run underneath the market clearing price of electricity. Whatever the price of gas, the CCGT is always in the money and will be economical to run under these circumstances. If gas prices go up, the CCGT will be more profitable, and if they go down it will be less profitable, but the volatility in profits with respect to changes in gas prices will be lower than that for coal or nuclear plants.

7. In 2000, the capacity factors for the nuclear plants in France were 76%, for those in Japan 79%, and for those in South Korea, 91%. Ideally, we would look at availability data, but except for France where nuclear accounts for such a large share of electricity supply that some plants must by cycled up and down, nuclear units are generally run full out when they are available (Source: Calculated from data on EIA web site.)

8. These numbers underestimate the true O&M costs of nuclear plants because they exclude administrative and general operating costs that are typically captured elsewhere in utility income statements. These overhead costs probably add another 20% to nuclear O&M costs. We do not consider these additional costs here because they are also excluded from the O&M costs for competing technologies. In a competitive power market, however, generating plants must earn enough revenues to cover these overhead costs as well as their direct capital and O&M costs.

9. That is, we are not considering competition between new nuclear plants and *existing* coal and gas plants (whose construction costs are now sunk costs). We recognize there may be economical opportunities to increase the capacity of some existing nuclear plants and to extend their commercial lives. We do not consider these opportunities here.

10. The reduced non-fuel O&M costs assumed are about 10 mills/kWh in the base case and compare favorably to 9 mills/kWh assumed by TVA (90% capacity factor) in its recent evaluation of the restart of Browns Ferry Unit #1.

11. Of course, in a competitive wholesale electricity market investors are free to act on such expectations by making financial commitments to build new nuclear plants. About 150,000 MWe of new generating capacity has been built in the U.S. in the last five years, most of it owned by merchant investors and most of it fueled by natural gas and none of it nuclear. See Paul L. Joskow, "The Difficult Transition to Competitive Electricity Markets in the U.S.," May 2003

12. We have seen some analyses that assume that nuclear plants will be financed with 100% government-backed debt, pay no income or property taxes, and have very long repayment schedules. One can make the costs of nuclear power look lower this way, but it simply hides the true costs and risks of the projects which have effectively been transferred to consumers and taxpayers.

13. This brings the nuclear plant cost down to $1500/kW. This is roughly the cost used in the analysis of the costs of a new nuclear power plant in Finland at current exchange rates. (However, the Finnish analysis assumes that the plant can be financed with 100% debt at a 5% real interest rate and would pay no income taxes). Note, however, that TVA estimates that the costs of *refurbishing* a mothballed unit at Browns Ferry will cost about $1300/kWe, and that recent Japanese experience is closer to the $2000/kWe base case assumption. TVA's analysis of the costs of refurbishing the Browns Ferry unit assume that the project can be financed with 100% debt at an interest rate 80 basis points above 10-year treasury notes and would pay no taxes.

14. Obviously, there is some set of assumptions that will make nuclear cheaper than coal. However, they basically require driving the construction costs and construction time profile to be roughly equivalent to those of a coal unit. We also have not assumed any improvements in construction costs or heat rates for coal units associated with advanced coal plant designs.

15. We have modeled the carbon "price" as a carbon dioxide emissions tax. However, the intention is to simulate any policies that give nuclear power "credit" relative to fossil fuel alternatives for producing no CO_2.

16. "Summary and Analysis of McCain-Leiberman 'Climate Stewardship Act of 2003'," William Pizer and Raymond Kopp, Resources for the Future, January 28, 2003.

Chapter 6 — Safety

Safe operations of the entire nuclear fuel cycle are a paramount concern. In this chapter we address reactor safety, the continuing availability of trained personnel for nuclear operations, the threat of terrorist attack, and nuclear fuel cycle safety, including nuclear fuel reprocessing plants.

There are about 100 nuclear power plants in the U. S., and over 400 in the world, mostly light water reactors (LWRs). With the benefit of experience and improved plant designs going into service, performance has improved over time to unit capacity factors[1] of 90% and higher in the U.S.[2] The means of improvement include independent peer review and the feedback of operating experience at reactor fleets worldwide, so that all operators become aware of mishaps that occur, and the commitment of plant owners and managements to the development of safety culture within the organizations that operate nuclear power plants. These actions and initiatives in training and qualification of reactor operators that have been implemented by organizations of plant owners[3] are major factors in the performance improvements. Experience also includes three serious reactor accidents[4] and several fuel cycle facility accidents.[5]

A number of events have occurred at reactors that were headed for an accident but stopped short. Such an event[6] came to light during an inspection of the Davis-Besse reactor vessel head in March, 2002, during reactor shutdown. The inspection disclosed a large cavity in the vessel head next to one of the reactor control rod drive mechanisms, caused by boric acid leakage and corrosion. The cavity seriously jeopardized reactor vessel integrity. Fortunately, the fault was discovered before restart of the reactor. This event discloses a failure on the part of the plant owners to respond to earlier indications of an issue and to look for problems in an early stage at their plant. It is still an open question whether the average performers in the industry have yet incorporated an effective safety culture into their conduct of business. The U.S. Nuclear Regulatory Commission shares responsibility in the matter, as it accepted delay of scheduled surveillance and inspection of vital primary system components. A major nuclear power initiative will not gain public confidence, if such failures occur.

With regard to the mandate of the Nuclear Regulatory Commission for safety of nuclear plants in the U. S., the Davis-Besse incident also raises questions about whether nuclear reactor safety goals are compatible with the transition to competitive electricity markets. On the one hand some observers suggest that unregulated generators will be more concerned with maximizing plant output and less willing to close plants for safety inspections and corrective actions where necessary. On the other hand, owners groups have long stated that nuclear plant operation conducted to ensure a high level of safety is also economically beneficial. Further, nuclear plant accident costs are not financially attractive for plant owners. While there may be some accident costs that are not fully internalized into decisions made by individual nuclear plant owners, the owner of a plant that has a serious accident would face very significant adverse financial consequences, as was the case of General Public Utilities after the accident at Three Mile Island Unit 2. We believe it is important to maintain the principle that the primary responsibility for safe operation of nuclear plants rests with the plant owners and operators, as the generation segment of the electric power industry is deregulated, and that the Nuclear Regulatory Commission should adapt its inspection activities, reporting requirements, and enforcement actions to reflect the new incentives created by competitive generation markets.

REACTOR SAFETY

The global growth scenario considered in this report is a three-fold increase in the world nuclear fleet capacity by 2050. The goal, of course, should be to carry out this large expansion without increasing the frequency of serious accidents. We believe this can be accomplished by means of both evolutionary and new technologies focused on LWRs.

Three major reasons for reducing the frequency of serious accidents are: first, and foremost, they are a threat to public health. Reactor core damage has the potential to release radioactivity to air and groundwater. Second, an accident destroys capital assets. Loss of a plant costs billions of dollars and could restrict electrical generating capacity in the locality until replacement, thereby adding to the economic loss. Third, a serious accident erodes public confidence in nuclear generation, with possible consequences of operating plant shutdowns, and/or moratoria on new construction.

What is the expected frequency of accidents today with the currently operating nuclear plants? There are two ways to determine the frequency of accidents: historical experience and Probabilistic Risk Assessment.[7] Since the beginning of commercial nuclear power in 1957, more than 100 LWR plants have been built and operated in the U.S., with a total experience of 2679 reactor-years through 2002. During this time, there has been one reactor core damage accident at Three Mile Island Unit 2. The core damage frequency of U.S. reactors is therefore 1 in 2679 reactor-years on average.

Probabilistic Risk Assessment (PRA) identifies possible failures that can occur in the reactor, e.g., pipe breaks or loss-of-reactor coolant flow, then traces the sequences of events that follow, and finally determines the likelihood of their leading to core damage. PRA includes both internal events and external events, i.e., natural disasters. Expert opinion using PRA considers the best estimate of core damage frequency to be about 1 in 10,000 reactor-years for nuclear plants in the United States. Although safety technology has improved greatly with experience, remaining uncertainties in PRA methods and data bases make it prudent to keep actual historical risk experience in mind when making judgments about safety.

With regard to implementation of the global growth scenario during the period 2005-2055, both the historical and the PRA data show an unacceptable accident frequency. The expected number of core damage accidents during the scenario with current technology[8] would be 4. We believe that the number of accidents expected during this period should be 1 or less, which would be comparable with the safety of the current world LWR fleet. A larger number poses potential significant public health risks and, as already noted, would destroy public confidence. We believe a ten-fold reduction in the likelihood of a serious reactor accident,[9] i.e., a core damage frequency of 1 in 100,000 reactor- years is a desirable goal and is also possible, based on claims of advanced LWR designers, that we believe plausible. In fact, advanced LWR designers claim that their plant designs already meet this goal, with even further reduction possible. If these claims and other plant improvements and cost reductions are verified, advanced LWRs will be in a very good position to drive a large share of the global growth scenario market.

For future LWR development, we recommend implementation of designs that use a combination of passive and active features in order to enhance reliability of plant safety systems. Passive systems utilize stored energy for pumping, either by means of pressurized tanks or by gravity acting on water in elevated tanks. They substitute for motor-driven pumps ultimately driven by emergency diesel generators, and can thereby remove the risk of failure of diesels to start when needed, i.e., during a station blackout.

Additional gains may come with the introduction of High-Temperature Gas Reactors (HTGRs). In principle the HTGR may be superior to the LWR in its ability to retain fission products in a loss-of- coolant accident, because of fuel form and because core temperatures can be kept sufficiently low due to low power density design and high heat capacity of the core, if RD&D validates this feature. Two HTGR plants of small capacity and modular design are under development for eventual commercial application.

We describe briefly deployment for the global growth scenario, first for LWRs, and then for HTGRs. Because of the experience base, construction of certified LWR designs at approved sites could begin within the year or two required for contractual arrangements, limited primarily by retooling of a dormant industry, and obtaining regulatory approvals under new licensing procedures. In order to build the global growth scenario capacity of 1000 GWe in 50 years, an average rate of construction of 20 to 25 plants[10] per year would be required, with greater numbers in later years. For historical comparison, LWR actual worldwide construction totaled about 400 plants over 25 years, for an average of 16 plants completed per year. Doubling the past rate of construction for this scenario is not an unreasonable projection, but remains a challenge, because plant construction time must also be reduced in order to reduce plant capital cost.

LWR experience does not exclude entry of the HTGR into the marketplace. However, it does focus attention on the lead times and costs associated with its development and the need for operating experience before commitment of capital investment and the large manufacturing expansion required to carry it out.

We believe that the lead time to carry out RD&D requirements for HTGR licensing, and at least several years of operation by one or more demonstration plants, will add up to 15 to 20 years before rapid, commercial deployment can be expected. Given this lead time, we expect that two thirds or more of the fleet through 2050 will be LWRs.

It is possible with success at every turn that HTGR deployment could make up as much as one third of the global growth scenario. The uncertainties in this projection are large, however, and a range of HTGR penetration from very small to a high of one third is realistic. We note that the plant capacity of the two HTGR concepts is in the range of 125-350 MWe, i.e., substantially smaller than LWR plants. This is a very attractive feature of HTGRs, if cost targets are met. Depending on the market shares of the two HTGR concepts, about 4 plants would be required to equal the output of a 1000 MWe LWR. If HTGR plants were to capture one third of the mid-century scenario, there would be about twice as many HTGRs as LWRs in 2050.

TRAINING AND QUALIFICATION OF PLANT MANAGEMENT AND STAFF

Realization of the mid-century scenario has important implications for safety, and especially in training and qualification of people competent to manage and operate the plants safely, including the supporting infrastructure necessary for maintenance, repair, refueling, and spent fuel management. Development of competent managers and identification of effective management processes is a critical element in achieving safe and economic nuclear power plant operations. For developed countries that now operate nuclear plants, these tasks require attention to the rejuvenation of the entire workforce.[11]

For developing countries, however, this challenge is much greater, because of the lack of workers in the many skills required in nuclear power plant construction, operations, and maintenance. The workforce must be trained and grow from a small or negligible base. There are two main models for realization of the necessary growth: first, "do it yourself," and second, the commercial mode of importing goods and services. The first takes time and is subject to error in the process of learning. The second is expensive in the long run and fails to create skills and provide jobs at home. The best path for most developing countries is likely to be some combination of the two models that yields both competence and jobs.

TERRORIST ATTACK ON NUCLEAR INSTALLATIONS

Terrorists have demonstrated their ability to inflict catastrophic damage. Nuclear facilities as potential targets have not escaped notice. On the one hand experts have concluded that civil works and security provisions make nuclear plants hard targets. On the other hand, the hazards are on a scale previously considered to be extremely rare in evaluation of severe reactor accidents. The question is what new security measures, if any, are appropriate? We believe there is no simple, one-size-fits-all answer. It depends on many factors including threat evaluation, plant location, facility design, and government security resources and practices.

Nuclear plant safety is a good starting point for the evaluation of security risk. What we conclude about plants also applies to other fuel cycle facilities. Nuclear plant safety has considered natural external events, such as earthquakes, tornadoes, floods, and hurricanes. Terrorist attack by fire or explosion is analogous to external natural events in its implication for damage and release of radioactivity. The strength of containment buildings and structures presents a major obstacle and hardened target for attack. The Electric Power Research Institute[12] carried out an evaluation of aircraft crash and NPP structural strength, concluding that U.S. containments would not be breached. The U.S. NRC is performing its own evaluation, including structural testing at Sandia National Laboratory, not yet complete.

A broad survey and evaluation of hazards and protective actions is in order to make decisions on adequate protection. Such a survey must begin by identifying possible modes of attack and vulnerabilities associated with designs and locations. It must also identify the cost effectiveness of a range of security options for new designs, old plants near decommissioning, and plants in mid-life. There is also a need for sharing information with governments of countries and supporting institutions that will undertake nuclear power programs in order to provide effective intelligence and security.

NUCLEAR FUEL CYCLE SAFETY

Realization of the global growth scenario entails construction and operation of many fuel cycle facilities around the world, such as those described in Chapter IV, and also the facilities and repositories associated with waste management. There are varying degrees of risk to public safety associated with these facilities, and therefore a need for systematic evaluation of risk on a consistent basis that takes into account evaluations performed heretofore on individual fuel cycle facilities.

The need for such an evaluation is especially important in the case of reprocessing plants. The United States does not have any commercial reprocessing plants. France, the United Kingdom and Japan have reprocessing plants in operation, based on aqueous PUREX separations technology and improvements to it over many years. Pyro-reprocessing and dry reprocessing R&D has been done with no commercial application as yet. Aqueous separation plants have high inventories of fission products, as well as fissile material of work in process, and many waste streams. Future improvements in separation technology may be capable of reducing radioactive material inventories, measured as a fraction of annual throughput, but inventories will continue to be large, because of the large annual product required, if and when reprocessing comes into wider commercial use many years in the future.

We are concerned about the safety of reprocessing plants,[13] because of large radioactive material inventories, and because the record of accidents, such as the waste tank explosion at Chelyabinsk in the FSU, the Hanford waste tank leakages in the United States and the discharges to the environment at the Sellafield plant in the United Kingdom. Releases due to explosion or fire can be sudden and widespread. Although releases due to leakage may take place slowly, they can have serious long-term public health consequences, if they are not promptly brought under control. Although the hazards of reprocessing plants differ from those of reactors, the concepts and methods and practices of reactor safety are broadly applicable to assuring the safety of reprocessing plants. We do not see the need for commercial reprocessing in the global growth scenario, but we believe the subject requires careful study,[14] and action, if and when reprocessing becomes necessary.

NOTES

1. Capacity factor is the ratio of actual annual plant electrical production and maximum annual production capability.
2. While worldwide capacity factors (around 75%) are lower than those recently achieved in the U.S., a similar trend of improved capacity factors is observed outside of the U.S. as well.
3. The Institute of Nuclear Power Operations in the U.S. and the World Association of Nuclear Operators worldwide.
4. Windscale, UK, gas-cooled reactor, graphite combustion due to graphite stored heat release, with limited release of radioactivity, 1952; TMI 2, PWR, loss-of-coolant, 20% core meltdown, and small release, 1979; Chernobyl, graphite-moderated, water-cooled reactor, reactivity accident with large external release of radioactivity and health effects, 1986.
5. Chelyabinsk, FSU, reprocessing waste explosion, (1957); Hanford, Washington State, waste storage tank leakage, (1970-); Sellafield, UK, reprocessing waste discharges into ocean, (1995-), Tokai-Mura, Japan, nuclear criticality incident in fuel fabrication, (1999). We know of no complete inventory of reprocessing accidents; such a survey is needed.
6. A similar event was discovered at a French nuclear power plant in 1991.
7. Three important references are: Reactor Safety Study, WASH 1400, U.S. Nuclear Regulatory Commission, October 1975; Severe Accident Risks, NUREG-1150, U.S. NRC, December 1990; and Individual Plant Examination Program, NUREG-1560, U.S. NRC, December 1997.
8. The number of core damage accidents expected is the product of the CDF and the reactor-years of experience. We assume a CDF of 10-4 and 40,000 reactor-years experience during the period of 2005 to 2055: the product is 4 accidents. The Safety Appendix 6 explains the relevant data in more detail.
9. Potentially large release of radioactivity from fuel accompanies core damage. Public health and safety depends on the ability of the reactor containment to prevent leakage of radioactivity to the environment. If containment fails, there would be a large, early release (LER) and exposure of people for some distance beyond the plant site boundary, with the amount of exposure depending on accident severity and weather conditions. The probability of containment failure, given core damage, is about 0.1. Hence the frequency of a LER is 1 in 1,000,000 years. LER is defined in U.S. NRC Regulatory Guide 1.174.
10. We expect individual plant capacities in the range of 600-1500 MWe. In developed countries the average plant capacity is expected to be about 1000 MWe, with a smaller average capacity in developing countries.
11. The workforce has been aging for more than ten years due to lack of new plant orders and decline of industrial activity.
12. Deterring Terrorism - Aircraft Crash Impact Analyses Demonstrate Nuclear Power Plant's Structural Strength; EPRI Study, Nuclear Energy Institute website, www.nei.org, December 2002.
13. A brief comparison of reprocessing plants with reactors shows that the historical accident frequency of reprocessing plants is much larger than reactors: three of the more significant accidents are cited in footnote 5. Furthermore, the number of reprocessing plant-years of operation is many fewer that in the case of reactors. Therefore the accident frequency of reprocessing plants is much higher.
14. We are not aware of PRA analyses of fuel cycle facilities; one exception is: *Status report on the EPRI fuel cycle accident risk assessment*, prepared by SAIC for EPRI report number NP-1128, July 1979.

Chapter 7 — Spent Fuel/High-Level Waste Management

The management and disposal of radioactive waste from the nuclear fuel cycle is one of the most difficult problems currently facing the nuclear power industry. Today, more than forty years after the first commercial nuclear power plant entered service, no country has yet succeeded in disposing of high-level nuclear waste – the longest-lived, most highly radioactive, and most technologically challenging of the waste streams generated by the nuclear industry.[1]

In most countries, the preferred technological approach is to dispose of the waste in repositories constructed in rock formations hundreds of meters below the earth's surface. Although several experimental and pilot facilities have been built, there are no operating high-level waste repositories, and all countries have encountered difficulties with their programs. The perceived lack of progress towards successful waste disposal clearly stands as one of the primary obstacles to the expansion of nuclear power around the world. [2]

THE GOALS OF NUCLEAR WASTE MANAGEMENT AND DISPOSAL

Spent nuclear fuel discharged from nuclear reactors will remain highly radioactive for many thousands of years. The primary goal of nuclear waste management is to ensure that the health risks of exposure to radiation from this material are reduced to an acceptably low level for as long as it poses a significant hazard. Protection against the risk of malevolent intervention and misuse of the material is also necessary.

Because of the very long toxic lifetime of the waste, the primary technical challenge is that of long- term isolation. However, shorter-term risks must also be addressed. Prior to final disposition, the waste will pass through several intermediate stages or operations, including temporary storage, transportation, conditioning, packaging, and, potentially, intermediate processing and treatment steps. There are several possible choices at each stage, and the design of the overall waste management system – including the specific technical characteristics and the physical location of each stage – will importantly affect the overall level of risk and its distribution over time. For example, waste management strategies involving the separation of individual radionuclides from the spent fuel could reduce long-term exposure risks, while elevating risks in the short term. Such interdependencies attest to the importance of an integrated approach to nuclear waste management decision-making, in which the system-wide impacts of individual decisions are fully considered.

What constitutes an acceptable level of exposure risk? The U.S. Environmental Protection Agency (EPA) has stipulated that the radiation dose from all potential exposure pathways to the maximally- exposed individual living close to a waste disposal site should not exceed 15 millirems per year for the first 10,000 years after final disposition. This is about twenty times less than the dose that individuals receive annually from natural background radiation on average. EPA has translated the 15 millirem per year standard into an annual risk of developing a fatal cancer of about 1 chance in 100,000.

Different radiation exposure standards apply to operating nuclear fuel cycle facilities.

The suitability of alternative waste management schemes must ultimately be judged in relation to these fundamental safety goals. Other measures of waste management system performance are frequently cited, such as the volume or mass of waste material generated, the total inventory of radioactivity in the waste, the amount of heat it emits, its radiotoxicity, and the solubility and mobility of specific radionuclides. Each of these metrics contains useful information about the technical requirements of individual components of the waste management system. But none of these metrics is an adequate proxy for the fundamental measure of waste management system performance — that is, the risk to human health from radiation exposure in the short and long term.

THE FEASIBILITY OF GEOLOGIC DISPOSAL

As already noted, most countries with nuclear power programs have stated their intention to dispose of their high-level waste in mined repositories, hundreds of meters below the earth's surface. The concept of deep geologic disposal has been studied extensively for several decades, and there is a high level of confidence within the expert scientific and technical community that this approach is capable of safely isolating the waste from the biosphere for as long as it poses significant risks.[3] This assessment is based on: (1) an understanding of the processes and events that could transport radionuclides from the repository to the biosphere; (2) mathematical models which, when combined with information about specific sites and repository designs, enable the long-term environmental impact of repositories to be quantified; and (3) natural analog studies which help to build confidence that the analytical models can be reliably extrapolated to the very long time-scales required for waste isolation.

We concur with the view that high-level waste can safely be disposed of in geologic repositories. As discussed below, we believe there are opportunities for advances in geologic and engineering system design that can provide additional assurance regarding the long-term performance of such repositories. We note, however, that among the general public, and even among some in the technical community, there is a lack of confidence in the prospects for successful technical and organizational implementation of the geologic disposal concept. Previous missteps and failures in the waste management programs of several countries have contributed to these doubts. Some members of the public – especially those living in the vicinity of proposed repository sites – also question the fairness and integrity of the site selection process.

MEASURES TO INCREASE THE LIKELIHOOD OF SUCCESSFUL IMPLEMENTATION OF WASTE MANAGEMENT AND DISPOSAL

We have examined several possible innovations that might facilitate the successful implementation of waste management and disposal. In order to make a difference, any such measure should have to contribute significantly to one or more of the following goals:

- ☐ reduction of the risks to public health and safety and the environment from waste management and disposal activities in the short and/or long term;
- ☐ reduction of the economic costs of achieving an acceptable level of performance with respect to short and long-term risk;
- ☐ increase of public confidence in the technical and organizational effectiveness of waste management and disposal activities.

The innovations we have considered can be grouped into three categories:

- ☐ technical modifications or improvements that could be incorporated into the once-through fuel cycle;

- technical modifications or improvements requiring a closed fuel cycle;
- institutional or organizational innovations.

It is important to emphasize that each innovation must be evaluated in terms of its impact on the entire waste management system, including not only final disposal but also pre-disposal processing, transportation, and storage operations. In the following paragraphs we summarize our findings concerning each category of innovations. More detailed discussions can be found in Appendix 7.

TECHNICAL MODIFICATIONS OR IMPROVEMENTS TO SPENT FUEL MANAGEMENT IN THE ONCE-THROUGH FUEL CYCLE

Extended interim storage of spent fuel Although most spent fuel destined for direct disposal will in practice be stored above ground for many years because of the protracted process of developing high level waste repositories, storage arrangements so far have mostly been ad hoc and incremental. We believe that a period of several decades of interim storage should be incorporated into the design of the spent fuel management system as an integral part of the system architecture.[4] Such a storage capability would:

- provide greater flexibility in the event of delays in repository development;
- allow a deliberate approach to disposal and create opportunities to benefit from future advances in relevant science and technology;
- provide greater logistical flexibility, with centralized buffer storage capacity facilitating the balancing of short and long-term storage requirements, and enabling the optimization of logistics, pre- processing, and packaging operations;
- allow countries that want to keep open the option to reprocess their spent fuel to do so without actually having to reprocess;
- create additional flexibility in repository design, since the spent fuel would be older and cooler at the time of emplacement in the repository; and
- potentially reduce the total number of repositories required.

At-reactor storage will be feasible for some spent fuel, even for several decades. For the remainder, centralized storage facilities will be required. Internationally, a network of safeguarded, well protected central storage facilities will also yield important non-proliferation benefits (see Chapter 8). The siting of temporary storage facilities will likely be difficult. Although the technical issues involved are more straightforward than for geologic repositories, the task of persuading affected communities to accept such facilities may be no less challenging. Nevertheless, making provision for several decades of temporary spent fuel storage would make for a more robust waste management system overall, and could be cost-effective too, if the result was to postpone the onset of major spending on repository construction and operation.

High burnup fuel The burnup of spent fuel – the amount of energy that has been extracted from a unit of fuel at the time of its discharge from the reactor – is a design choice for reactor operators. In the past, the burnup of LWR fuel averaged about 33 MWD/kg. An increase to 100 MWD/kg is within technical reach, and even greater increases are potentially achievable.

Increasing the burnup to 100 MWD/kg would yield a threefold reduction in the volume of spent fuel to be stored, conditioned, packaged, transported, and disposed of per unit of electricity generated. The corresponding reduction in the required repository storage volume would be more modest; the individual fuel assemblies, although there would be fewer of them, would generate more decay heat and would therefore have to be spaced farther apart in the repository. The amount of plutonium and other actinides, which are the dominant contributors to the radiotoxicity of the spent fuel after the first hundred years or so, would also be reduced somewhat per unit of electricity generated. A further benefit of higher burnup is that the isotopic composition of the discharged plutonium would make it less suitable for use in nuclear explosives.[5]

It is important to note, however, that the present pricing structure for nuclear waste management services in the United States – a standard fee of one-tenth of a cent payable to the government on each kilowatt hour of nuclear electricity generated — provides no economic incentive for nuclear generators to move in the direction of higher burnup. No discount is provided for the reduced volume of spent fuel and the safety, proliferation resistance, and economic benefits associated with higher burnup.[6]

Advances in geologic repository design A geologic repository must provide protection against every plausible scenario in which radionuclides might reach the biosphere and expose the human population to dangerous doses of radiation. Of all possible pathways, the one receiving most attention involves groundwater seeping into the repository, the corrosion of the waste containers, the leaching of radionuclides into the groundwater, and the migration of the contaminated groundwater towards locations where it might be used as drinking water or for agricultural purposes. Although the details differ, all proposed repository designs adopt a 'defense in depth' approach to protecting against this scenario, relying on a combination of engineered components and natural geologic, hydrologic, and geochemical barriers to contain the radionuclides.

The engineered barriers, broadly defined to include those physical and chemical features of the near- field environment that affect the containment behavior of the waste packages, have an important role to play in the overall performance of the repository. To date there has not been an adequate technical basis for the selection and development of the engineered barriers in the context of the overall multi- barrier system.

In siting a repository, it is important to select a geochemical and hydrological environment that will ensure the lowest possible solubility and mobility of the waste radionuclides. The geochemical conditions in the repository host rock and surrounding environment strongly affect radionuclide transport behavior. For example, several long-lived radionuclides that are potentially important contributors to long-term dose, including technetium-99 and neptunium-237, are orders of magnitude less soluble in groundwater in reducing environments than under oxidizing conditions.

Alternative disposal technologies: The deep borehole approach An alternative to building geologic repositories a few hundred meters below the earth's surface is to place waste canisters in boreholes drilled into stable crystalline rock several kilometers deep. Canisters containing spent fuel or high-level waste would be lowered into the bottom section of the borehole, and the upper section – several hundred meters or more in height – would be filled with sealant materials such as clay, asphalt, or concrete. At depths of several kilometers, vast areas of crystalline basement rock are known to be extremely stable, having experienced no tectonic, volcanic or seismic activity for billions of years.

The main advantages of the deep borehole concept relative to mined geologic repositories include: (a) a much longer migration pathway from the waste location to the biosphere; (b) the low water content, low porosity and low permeability of crystalline rock at multi-kilometer depths; (c) the typically very high salinity of any water that is present (because of its higher density, the saline water could not rise convectively into an overlying layer of fresh water even if heated); and (d) the ubiquity of potentially suitable sites.

An initial screening suggests that most of the countries that are likely to employ nuclear power in our global growth scenario may have geology appropriate for deep waste boreholes. Co-location of boreholes with reactor sites is a possibility. Suitable host rock also occurs beneath the sea floor. For this reason the concept may be particularly interesting for densely populated countries like Japan, Korea, and Taiwan. Since most of the power reactors in these countries (and indeed in most countries) are located on or close to the coast, the possibility arises of constructing artificial offshore islands which would be ideal sites from which to drill beneath the seabed and which could also serve as temporary storage venues for the spent fuel, obviating the need for on-land waste transportation and storage.

The overall system cost of deep borehole disposal using conventional drilling technology is uncertain, but according to one estimate would be comparable to that of mined geologic disposal.[7] Advances in technology could reduce the cost of drilling significantly. But since drilling alone accounts for only a relatively small fraction of the overall costs, the opportunities for savings are limited. A more important economic advantage may derive from the modularity of the deep borehole concept and the more flexible siting strategy that it allows. [8]

Implementing the deep borehole scheme would require the development of a new set of standards and regulations, a time-consuming and costly process. A major consideration would be the difficulty of retrieving waste from boreholes if a problem should develop (though the greater difficulty of recovering the plutonium in the waste might also be an advantage of the borehole scheme). Current U.S. regulatory guidelines for mined repositories require a period of several decades during which the high level waste should be retrievable. This would be difficult and expensive to ensure in the case of deep boreholes, though probably not impossible. Moreover, at the great depths involved, knowledge of in situ conditions (e.g., geochemistry, stress distributions, fracturing, water flow, and the corrosion behavior of different materials) will never be as comprehensive as in shallower mined repository environments. Recovery from accidents occurring during waste emplacement – for example, stuck canisters, or a collapse of the borehole wall – is also likely to be more difficult than for corresponding events in mined repositories. Finally, despite the order of magnitude increase in the depth of waste emplacement, it is difficult to predict the impact on public opinion of a shift in siting strategy from one large central repository to scores of widely dispersed boreholes.

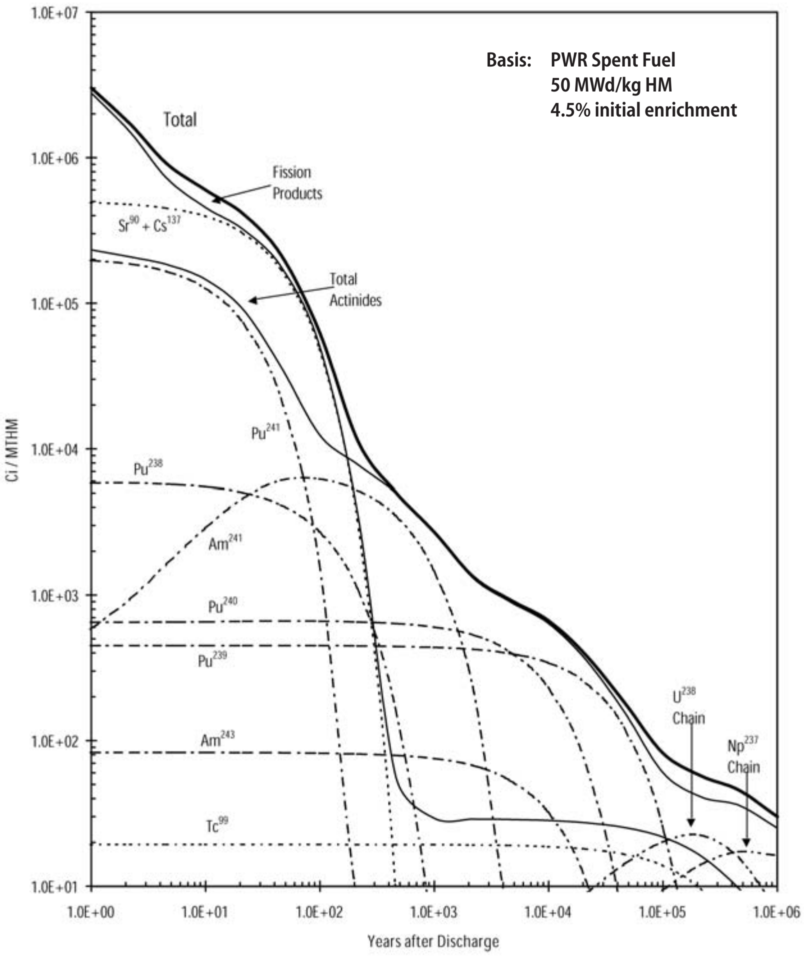
Despite these obstacles, we view the deep borehole disposal approach as a promising extension of geological disposal, with greater siting flexibility and the potential to reduce the already very low risk of long-term radiation exposure to still lower levels without incurring significant additional costs.

TECHNICAL MODIFICATIONS REQUIRING A CLOSED FUEL CYCLE

We next consider a set of waste management options involving the extraction of radionuclides from the spent fuel. The motivations for waste separation can be inferred from Figures 7.1, 7.2, and 7.3. At different times, different radionuclides are the dominant contributors to overall radioactivity and radiotoxicity and to the radioactive decay heat emitted by the fuel. Partitioning the spent fuel into separate radionuclide fractions and managing each fraction according to its particular characteristics could create additional flexibilities and new opportunities to optimize the overall waste management system. Partitioning also creates the opportunity to transmute the most troublesome radionuclides into more benign species. Thermal reactors, fast reactors, and accelerators have all been investigated as candidate transmutation devices, both individually and in combination.

Decisions about partitioning and transmutation must also consider the incremental economic costs and safety, environmental, and proliferation risks of introducing the additional fuel cycle stages and facilities necessary for the task.[9] These activities will be a source of additional risk to those working in the plants, as well as the general public, and will also generate con-

Figure 7.1 Radioactivity profile of spent fuel (curies/MTHM)



siderable volumes of non-high- level waste contaminated with significant quantities of transuranics. Much of this waste, because of its long toxic lifetime, will ultimately need to be disposed of in high-level waste repositories. Moreover, even the most economical partitioning and transmutation schemes are likely to add significantly to the cost of the once-through fuel cycle.[10]

We first consider the option of waste partitioning alone, and then the combination of partitioning and transmutation.

Waste partitioning Two fission products, strontium-90 and cesium-137, each with half-lives of about 30 years, account for the bulk of the radioactivity and decay heat in spent fuel starting a few years after discharge and for the next several decades. Thereafter, the actinides as a group become the dominant contributors to decay heat and radiotoxicity, with different actinides dominating at different times.

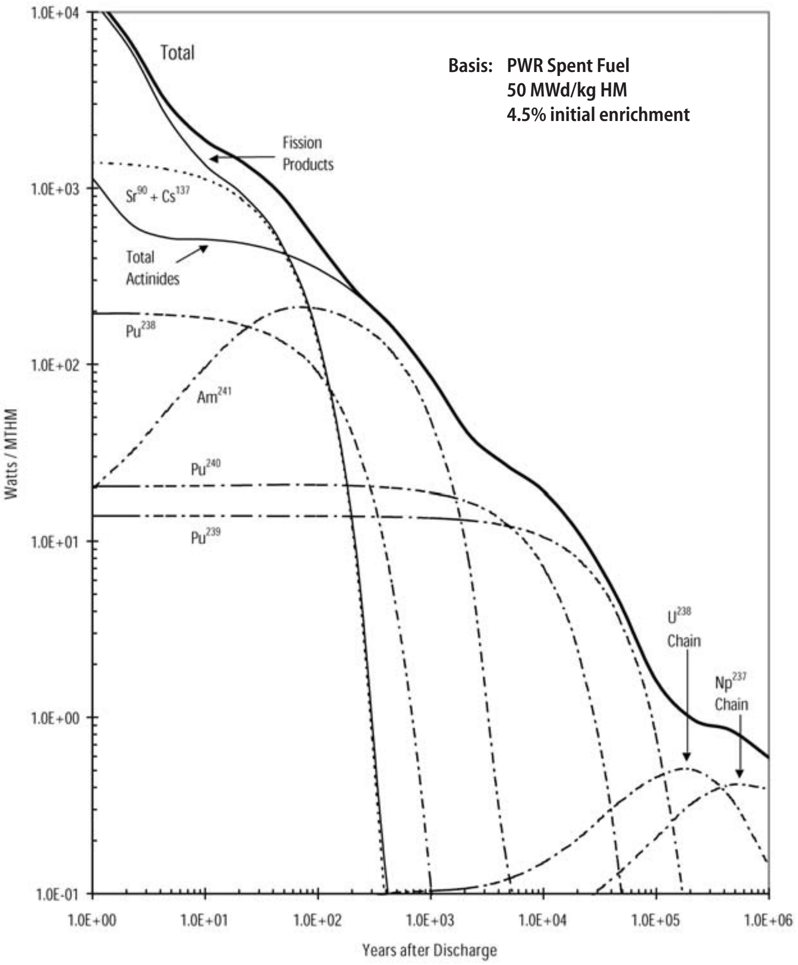
Extracting the high-heat-emitting fission product radionuclides from the spent fuel and storing them separately would allow the remainder of the radionuclides to occupy a more compact volume in a geologic repository, perhaps even reducing the total number of repositories required. It should be noted, however, that a similar result could be achieved without the need for separation by storing the spent fuel for several decades to allow the fission products to decay. In this case, moreover, there would be no need for a separate storage facility for the partitioned strontium-90 and cesium-137, which would have to be isolated from the biosphere for several hundred years before radioactive decay would render them harmless.

An alternative strategy would be to partition the uranium, plutonium and the other actinides from the spent fuel. If actinide partitioning were implemented in conjunction with interim waste storage for long enough to allow the strontium-90 and cesium-137 to decay significantly before repository emplacement, the effective storage capacity of a given repository could be increased many-fold. But the partitioned actinides would still have to be stored in a separate repository (or alternatively in deep boreholes). Moreover, by separating the actinides from the more radioactive fission products, the radiation barrier against unauthorized recovery of weapons-usable plutonium would be reduced relative to the case of intact spent fuel, at least for a century or so.

The case for partitioning the spent fuel and separately storing the different radionuclide fractions does not seem persuasive, especially given the additional costs and near-term environmental and safety risks associated with partitioning operations.

Waste partitioning and transmutation Waste partitioning strategies potentially become more attractive when combined with transmutation. There are three principal motivations for partitioning/transmutation schemes. First, if the long-lived isotopes in the waste could be extracted and destroyed, many more locations might become suitable candidates to host a repository for the remaining material. Indeed, if *all* of the long-lived radionuclides could be removed and destroyed, a disposal strategy relying solely on engineered structures for radionuclide containment might become feasible. The actinides, which as a group dominate the radiotoxicity of the spent fuel after about 100 years (see Figure 7.3), are usually cited as the prime candidates for partitioning and transmutation. However, performance assessments of the proposed repository sites at Yucca Mountain and at Olkiluoto in Finland show that long-lived fission products, such as technetium-99 and iodine-129, are more important than most actinides as sources of long-term exposure risk.[11] Partitioning and transmutation studies have yet to show that these fission products can be dealt with effectively. Even for the actinides, the technology is not yet available to remove these isotopes from all fuel cycle waste streams, and complete elimination of these isotopes from secondary, as well as primary waste streams, is unlikely ever to be attractive on economic grounds.

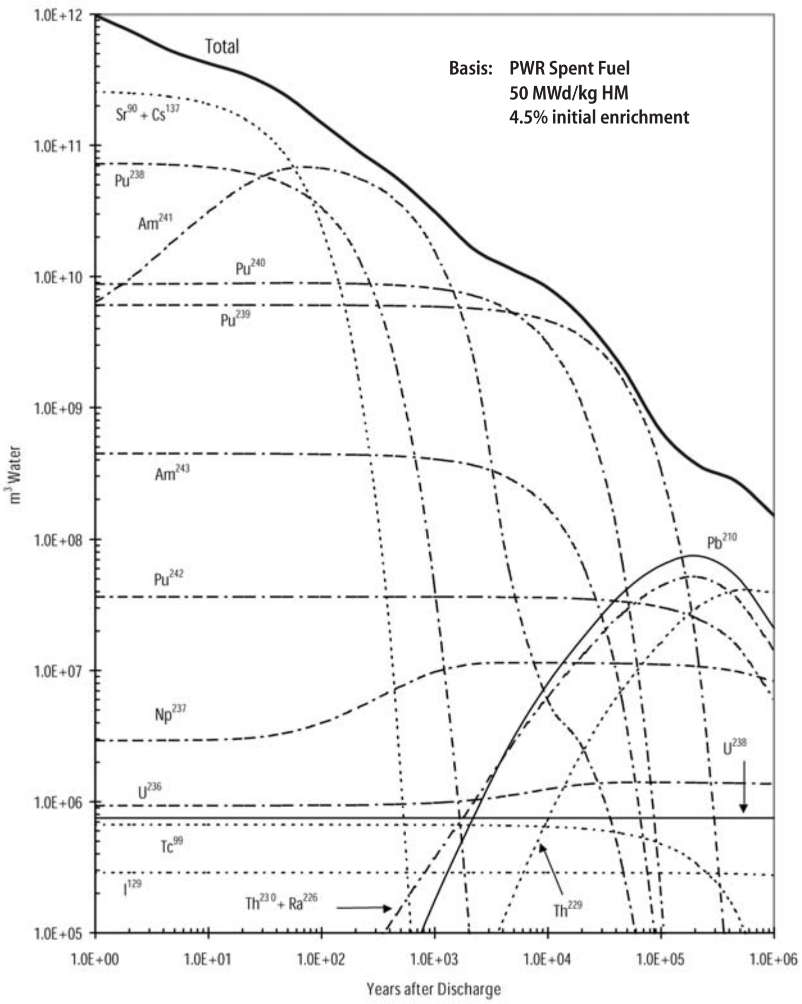
Figure 7.2 Decay Heat Profile of Spent Fuel



A second motivation for partitioning and transmutation is to reduce the thermal load on the repository, thereby increasing its storage capacity. As Figure 7.2 shows, after 60–70 years, the actinides are the dominant contributors to waste heating. As previously noted, actinide partitioning and transmutation, combined with a period of several decades of interim storage prior to final disposal of the residual waste, could increase the effective storage capacity of a given repository several-fold. Given the extreme difficulty of repository siting in most countries, any reduction in the required number of repositories must be counted as a significant gain, although this would be at least partly offset by the additional difficulty of siting the necessary waste partitioning and related fuel cycle facilities. As noted above, a less costly way to increase the effective storage capacity of repositories would simply be to defer waste emplacement until more of the heat-emitting radionuclides have decayed. In some countries, moreover, especially those with relatively small nuclear programs, a single repository is likely to be able to accommodate the entire national inventory of high-level waste even without actinide partitioning.[12]

A third motivation for partitioning and transmutation is to eliminate the risk that plutonium could later be recovered from a repository and used for weapons. It is difficult to assess the significance of this result. The value today of elim-

Figure 7.3 Radiotoxicity Index for 1MT of Spent Fuel



inating the technical means for one particular type of aggressive or malevolent human behavior centuries or millennia from now, out of all possible opportunities for such behavior that may exist at that time, is a question perhaps better addressed by philosophers than engineers, political scientists, or economists. From a narrowly technical perspective the best that can be said is that, without partitioning and transmutation, the feasibility of plutonium recovery from a repository will increase with time, as the radiation barrier created by the fission products in the waste decays away.

Against these putative long-term benefits of waste partitioning and transmutation must be weighed the increased short-term health, safety, environmental, and security risks involved. All actinide partitioning and transmutation schemes currently under consideration also seem likely to add significantly to the economic cost of the nuclear fuel cycle.

The trade-off between reduced risk over very long time scales and increased risk and cost in the short term is an issue on which reasonable people can disagree. The evaluation can furthermore be expected to vary by country, reflecting the different preferences and different constraints – geological, demographic, political, economic – of different societies. *Nevertheless, taking all these factors into account, we do not believe that a convincing case can be made on the basis of waste management considerations alone that the benefits of advanced fuel cycle schemes featuring waste partitioning and transmutation will outweigh the attendant risks and costs.* Future technology developments could change the balance of expected costs, risks, and benefits. For our fundamental conclusion to change, however, not only would the expected long-term risks from geologic repositories have to be significantly higher than those indicated in current risk assessments, but the incremental costs and short-term safety and environmental risks would have to be greatly reduced relative to current expectations and experience.

Some argue that partitioning and transmutation, by reducing the toxic lifetime of the waste, could change public attitudes towards the feasibility and acceptability of nuclear waste disposal. There is no empirical evidence of which we are aware to support this view. Our own judgment is that local opposition to waste repositories or waste transportation routes would not be much influenced, even if the toxic lifetime were reduced from hundreds of thousands to hundreds of years.

Our assessment of alternative waste management strategies leads to the following important conclusion: *technical improvements to the waste management strategies in the once-through fuel cycle are potentially available that could yield benefits at least as large as those claimed for advanced* *fuel cycles featuring waste partitioning and transmutation, and with fewer short-term risks.* The most that can reasonably be expected of partitioning and transmutation schemes is to reduce the inventory of actinides in geologic repositories by perhaps two orders of magnitude.[13] Reductions of two orders of magnitude or more in long-term radiation exposure risks could potentially be achieved by siting the repositories in host environments in which chemically reducing conditions could be ensured. Moreover, deep borehole technology offers a credible prospect of risk reductions of several orders of magnitude relative to mined repositories. Neither of these options is likely to cost as much or take as long to develop and deploy as waste partitioning and transmutation schemes.

INSTITUTIONAL INNOVATIONS

Technological advances can increase the likelihood that nuclear waste disposal will be successfully implemented. But an equally important consideration is the competence of the implementing authorities. A major challenge for these authorities under our global growth scenario will be to find suitable disposal sites. A worldwide deployment of one thousand 1000 megawatt LWRs operating on the once-through fuel-cycle with today's fuel management characteristics would generate roughly three times as much spent fuel annually as does today's nuclear power plant fleet.[14] If this fuel was disposed of directly, new repository storage capacity equal to the currently planned capacity of the Yucca Mountain facility would have to be created somewhere in the world roughly every three or four years. For the United States, a three-fold increase in nuclear generating capacity would create a requirement for a Yucca Mountain equivalent of storage capacity roughly every 12 years (or every 25 years if the physical rather than the legal capacity limit of Yucca Mountain is assumed.) Even if the technical strategies discussed above succeed in reducing the demand for repository capacity, the organizational and political challenges of siting will surely be formidable.

Today the political and legal mechanisms for balancing broad national policy goals against the concerns of affected local communities in the site selection process vary widely, even among the democratic societies of the West. This diversity of approaches will surely persist, although over time, as some nations achieve success in gaining local acceptance of repositories, some international diffusion of 'best siting practices' is probable. On present evidence, these best practices seem likely to include full access to information, opportunities for broad-based and continuing local community participation in consensus-building processes, the adoption of realistic and flexible schedules, and a willingness not merely to compensate local communities for hosting facilities, but also to find ways to make them actually better off.

Another important requirement for successful waste management implementation is the effective administration of a large-scale industrial operation involving the transportation, storage, processing, packaging, and emplacement of large quantities of radioactive waste. In the United States, as a matter of law and policy, the governance and management structure of the high-level waste program has been heavily focused on the development of the Yucca Mountain project. The scientific and engineering effort has also been almost exclusively focused on the investigation of the Yucca Mountain site and the development of a repository design for that site. However, the organizational and managerial demands of repository siting – a one-time project that is by definition exploratory, developmental, and, inevitably, highly politicized – are fundamentally different from the demands of a routine-based large-scale industrial processing and logistics operation. The intense focus on the Yucca Mountain project will continue as design and licensing activities gain momentum over the next few years. *In addition, the U.S. high level waste management program will require (1) a broadly-based, long-term R&D program, and (2) a separate organization for managing the operations of the waste management system.*

Finally, we note that international cooperation in the field of high-level waste management and disposal is presently under-developed. Stronger international coordination of standards and regulations for waste transportation, storage, and disposal will be necessary in order to strengthen public confidence in the safety of these activities. There is also considerable potential for international sharing of waste storage and disposal facilities. This might not only reduce proliferation risks from the fuel cycle (as discussed in the following chapter), but could also yield significant economic and safety benefits, although formidable political obstacles will have to be overcome first.

The authors of this study wish to acknowledge the valuable research support provided by our former students, Dr. Brett Mattingly and Dr. David Freed in the preparation of this chapter.

NOTES

1. In this study we focus on spent fuel and reprocessed high-level waste, since these waste types contain most of the radioactivity generated in the nuclear power fuel cycle and pose the greatest technical and political challenges for final disposal. We also include in the discussion so-called TRU waste — non-high-level waste contaminated with significant quantities of long-lived transuranic radionuclides — which because of its longevity will likely be disposed of in the same facilities as high-level waste. Other types of nuclear waste, including low-level waste and uranium mill tailings, are generated in larger volumes in the nuclear fuel cycle but pose fewer technical challenges for disposal, although localized opposition to disposal facilities for these materials has sometimes been intense.
2. In the opinion survey commissioned for this study, almost two-thirds of respondents did not believe that nuclear waste could be safely stored for long periods.
3. According to one recent international scientific assessment, "[I]n a generic way, it can be stated with confidence that deep geologic disposal is technically feasible and does not present any particularly novel rock engineering issues. The existence of numerous potentially suitable repository sites in a variety of host rocks is also well established." (International Atomic Energy Agency, "Scientific and Technical Basis for the Geologic Disposal of Radioactive Wastes", Technical Report No. 413, IAEA, Vienna, 2003.) Another expert group, convened by the OECD's Nuclear Energy Agency, found that, "[T]here is today a broad international consensus on the technical merits of the disposal of long-lived radioactive waste in deep and stable geologic formations…. Currently, geologic disposal can be shown to have the potential to provide the required level and duration of isolation." "The Environmental and Ethical Basis of Geologic Disposal of Long-Lived Radioactive Wastes: A Collective Opinion of the Radioactive Waste Management Committee of the OECD Nuclear Energy Agency,"1995 at http://www.nea.fr/html/rwm/reports/1995/geodisp.html . Yet another recent international assessment, this time under the auspices of the U.S. National Academy of Sciences, found that, "geological disposal remains the only scientifically and technically credible long-term solution available to meet the need for safety without reliance on active management…a well-designed repository represents, after closure, a passive system containing a succession of robust safety barriers. Our present civilization designs, builds, and lives with technological facilities of much greater complexity and higher hazard potential." See National Academy of Sciences,Board on Radioactive Waste Management, *Disposition of High Level Waste and Spent Nuclear Fuel: The Continuing Societal and Technical Challenges,* National Academy Press, Washington, D.C., 2001.
4. Because of the high heat generation, spent fuel must be stored for at least five years before it can be emplaced in a geologic repository. After another 30 years, the decay heat from the fission products Cs-137 and Sr-90, the leading sources of heat during this period, will have halved. After 100 years, the contribution from these isotopes will have declined by more than 90%. At that point, the fission product radiation barrier, which until then would complicate attempts by would-be proliferators to recover plutonium from the spent fuel, will have largely dissipated, and storage in relatively accessible surface or near-surface facilities thereafter would be less desirable on non-proliferation grounds.

5. As the burnup increases, the proportion of plutonium-239 in the plutonium declines, while the proportion of Pu-238 increases. For example, an increase in the burnup of PWR fuel from 33 MWD/kg to 100 MWD/kg would result in a decline in the Pu-239 content from 65% to 53%, while the Pu-238 content would increase from 1% to about 7%. (Zhiwen Xu, Ph.D. dissertation, Department of Nuclear Engineering, M.I.T., 2003). Pu-238 is a particularly undesirable isotope in nuclear explosives because of its relatively high emission rate of spontaneous fission neutrons and decay heat. According to some specialists, a Pu- 238 content above about 6% would make plutonium essentially unusable for weapons purposes. The denaturing effect of Pu-238 would be limited to a couple of centuries, however, because of its relatively short (87-year) half-life.

6. In recent years the average burnup of LWR fuel has risen from about 33 MWD/kg to about 45–50 MWD/kg. LWR operators have taken this step for economic reasons that are largely unrelated to waste disposal; the higher-burnup fuel cycle allows the reactors to operate for longer periods between refueling, thus increasing the reactor capacity factor.

7. Weng-Sheng Kuo, Michael J. Driscoll, and Jefferson W. Tester, "Re-evaluation of the deep drillhole concept for disposing of high-level nuclear wastes," *Nuclear Science Journal*, vol. 32, no. 3, pp. 229–248, June 1995.

8. According to one recent estimate, a full-scale 4-kilometer deep borehole could be drilled and cased in less than 5 months, at a cost of about $5 million. Tim Harrison, "Very Deep Borehole: Deutag's Opinion on Boring, Canister Emplacement and Retrievability", Swedish Nuclear Fuel and Waste Management Co., R- 00-35, May 2000.

9. See, for example, National Academy of Sciences, *Nuclear Wastes: Technologies for Separation and Transmutation, Committee on Separations Technology and Transmutation Systems*, National Research Council, Washington, D.C., 1996; B.Brogli and R. A. Krakowski, "Degree of sustainability of various nuclear fuel cycles," Paul Scherrer Institut Nuclear Energy and Safety Research Department, PSI Bericht No. 02-14, August 2002.

10. The PUREX/MOX fuel cycle currently practiced in several countries is one variant of the waste partitioning/transmutation option, in which uranium and plutonium isotopes are partitioned from the spent fuel, and the separated plutonium isotopes are partially transmuted into shorter-lived fission products in light water reactors. As shown in Appendix 5D, PUREX/MOX increases the fuel cycle cost to 4.5 times the once-through fuel cycle cost, depending on various assumptions.

11. To determine which radionuclides should be the principal targets of partitioning and transmutation, it is necessary to assess the likelihood that individual radionuclides will be transported from the repository to the biosphere. This in turn is a function of the particular geochemical and hydrological characteristics of the repository environment. In the oxidizing conditions characteristic of Yucca Mountain, the dominant contributors to long-term exposure risk are neptunium-237 and technetium-99. During the first 70,000 years, technetium-99 is the leading contributor, and between 100,000 years and 1 million years, the dominant isotope is Np-237. The peak dose of about 150 millirems/year (about half the background dose) occurs after about 400,000 years. (See: *Final Environmental Impact Statement for Yucca Mountain Repository*, February 2002) In contrast, a performance assessment of the proposed Finnish repository at Olkiluoto, in crystalline rock in a chemically reducing environment, concludes that the actinides would contribute very little to long-term dose, and that the dominant contributors would be a few long-lived fission products. The projected peak dose, moreover, is three orders of magnitude lower than that at Yucca Mountain (see Vieno and Nordman, "Safety Assessment of Spent Fuel Disposal in Hastholmen, Kivetty, Olkiluoto and Romuvaara - TILA-99," POSIVA 99-07, March 1999, ISBN 951-652-062-6).

12. For the repository at Yucca Mountain, operating in the so-called higher-temperature operating mode, the total subsurface area that would be required to accommodate the legal limit of 70,000 MT of spent fuel equivalent (including 7000 MT of defense high level waste) would be 1150 acres, equivalent to a square roughly 2 kilometers along a side. U.S. Department of Energy, "Yucca Mountain Science and Engineering Report, Rev. 1", DOE/RW-0539-1, February 2002, Executive Summary, at http://www.ymp.gov/documents/ser_b/. The current fleet of U.S. reactors is expected to discharge at least 105,000 MT of spent fuel and possibly considerably more, depending on reactor operating lifetimes. The 70,000 MTHM capacity limit at Yucca Mountain was politically determined, and according to some knowledgeable observers the physical storage capability of the site would be at least twice as large.

13. Nuclear Energy Agency, *Accelerator-Driven Systems and Fast Reactors in Advanced Fuel Cycles: A Comparative Study,* OECD, 2002 (available at http://www.nea.fr/html/ndd/reports/2002/nea3109.htm.

14. If each reactor has a burn-up of 50,000 MWth-d/MTHM , a capacity factor of 0.9, and a thermal efficiency of 33%, deployment of 1000 1 Gwe reactors would result in an annual spent fuel discharge of about 20,000 metric tons per year.

Chapter 8 — Nonproliferation

Nuclear weapons proliferation has been prominent in discussions about nuclear power since its earliest days. The birth of nuclear technology that began with production of the first weapons-usable fissionable material — plutonium production in nuclear reactors and high-enriched uranium by isotope enrichment — assured that this would be so. *Today, the objective is to minimize the proliferation risks of nuclear fuel cycle operation*. We must prevent the acquisition of weapons-usable material, either by diversion (in the case of plutonium) or by misuse of fuel cycle facilities (including related facilities, such as research reactors or hot cells) and control, to the extent possible, the know-how about how to produce and process either HEU (enrichment technology) or plutonium.

This proliferation concern has led, over the last half century, to an elaborate set of international institutions and agreements, none of which have proved entirely satisfactory. The Nuclear Nonproliferation Treaty (NPT) is the foundation of the control regime, since it embodies the renunciation of nuclear weapons by all signatories except for the declared nuclear weapons states – the P-5 (the United States, Russia, the United Kingdom, France, China) — and a commitment to collaborate on developing peaceful uses of nuclear energy. However, non-signatories India and Pakistan tested nuclear weapons in 1998, and signatories, such as South Africa and North Korea, have admitted to making nuclear weapons.

The International Atomic Energy Agency (IAEA) has responsibility for verifying NPT compliance with respect to fuel cycle facilities through its negotiated safeguards agreements with NPT signatories. The IAEA's safeguard efforts, however, are seriously constrained by the scope of their authorities (as evidenced in Iraq, Iran, and North Korea during the last decade), by their allocation of resources, and by the growing divergence between responsibilities and funding. The United Nations Security Council has not yet established a procedure or shown a willingness to impose sanctions when IAEA safeguards agreements are violated. A variety of multilateral agreements, such as the Nuclear Supplier Group guidelines for export control, aim to restrict the spread of proliferation-enabling nuclear and dual-use technology. European centrifuge enrichment technology, however, is known to have contributed to weapons development elsewhere, and the US and Russia have a continuing dispute over transfer of Russian fuel cycle technologies to Iran (a NPT signatory). This is not to say that the safeguards regime has failed to restrain the spread of nuclear weapons; it almost certainly has. Nevertheless, its shortcomings raise significant questions about the wisdom of a global growth scenario that envisions a major increase in the scale and geographical distribution of nuclear power.

In addition to the risk of nuclear weapons capability spreading to other nations, the threat of acquisition of a crude nuclear explosive by a sub-national group has arisen in the aftermath of the September 11, 2001 terrorist attacks. The report of interest in nuclear devices by the terrorist Al Qaeda network especially highlights this risk. Terrorist or organized crime groups are not expected to be able to produce nuclear weapons material themselves; the concern is their direct acquisition of nuclear materials by theft or through a state sponsor. This places the spotlight on the PUREX/MOX fuel cycle as currently practiced in several countries, since the fuel cycle produces during conventional operation nuclear material that is easily made usable for a weapon. The sub-national theft risk would be exacerbated by the spread of the PUREX/MOX fuel cycle, particularly to those countries without the infrastructure for assuring stringent control and accountability.

A separate concern is the dirty bomb threat in which radioactive material (from any source, such as nuclear spent fuel or cobalt sources used in medicine and industry) is dispersed in a conventional explosive as a weapon of mass disruption. The dirty bomb threat is a very serious security concern but is not specific to the nuclear fuel cycle and will not be discussed further in the proliferation context.

It is useful to set a scale for the proliferation risk that has emerged from nuclear power operation to date. Spent fuel discharged from power reactors worldwide contains well over 1000 tonnes of plutonium. While the plutonium is protected by the intense radioactivity of the spent fuel, the PUREX chemical process most commonly used to separate the plutonium with high purity, is well known and described in the open literature. With modest nuclear infrastructure, any nation could carry out the separation at the scale needed to acquire material for several weapons. Further, the MOX fuel cycle has led to an accumulation of about 200 tonnes of separated plutonium in several European countries, Russia and Japan. This is equivalent to 25,000 weapons using the IAEA definition of 8 kg/weapon. Separated plutonium is especially attractive for theft or diversion and is fairly easily convertible to weapons use, including by those sub-national groups that have significant technical and financial resources.

The nonproliferation issues arising from the global growth scenario are brought into sharp focus by examining a plausible scenario for the deployment of 1000 GWe nuclear capacity (see Table 3.2 and Appendix 2). An important characteristic of this scenario is that much of the deployment would be expected in industrialized countries that either already have nuclear weapons, thus making materials security against theft the principal issue, or are viewed today as minimal proliferation risks. The concern about these nations' ability to provide security for nuclear material is especially elevated for Russia, whose economic difficulties have limited its effort to adopt strong material security measures; the concern applies to materials from both the weapons program and the fuel cycle,[1] which have significant inventories of separated Pu. Moreover geopolitical change, for example, in East Asia, could change the interests of some nations in acquiring nuclear capability. Japan, South Korea, and Taiwan have advanced nuclear technology infrastructures and over several decades might adjust to the emergence of China as both a nuclear weapons state and a regionally dominant economic force by seeking nuclear capability. North Korea provides a further complication to this dynamic.

The developing world might plausibly account for about a third of deployed nuclear power in the mid-century scenario. An appreciable part of this will likely be in China and India, which already have nuclear weapons and dedicated stockpile facilities and thus are not viewed as the highest risks for fuel cycle diversion. Nevertheless, dramatic growth of nuclear power in the sub-continent could be a pathway for nuclear arsenal expansion in India and Pakistan. The security of their nuclear enterprises remains of concern.

On the other hand, a number of other nations with relatively little nuclear infrastructure today, such as the Southeast Asian countries Indonesia, Philippines, Vietnam, and Thailand (with a 2050 projected combined population over 600 million) are also likely candidates for nuclear power in the global growth scenario. Iran is actively pursuing nuclear power, with Russian assistance, even though it has vast unexploited reserves of natural gas and could clearly meet its electricity needs more economically and rapidly by using this domestic resource. The United States in particular has argued that this indicates Iranian interest in acquiring a nuclear weapons capability, even though Iran is an NPT signatory and has a safeguards agreement with the IAEA in place. Recent revelation of the spread of clandestine centrifuge enrichment and heavy water technology exacerbates this concern. Thus the U.S. is arguing that cooperation with Iran on nuclear power should cease irrespective of the NPT's call for cooperation in the peaceful use of nuclear energy (Article IV). This issue has been a significant irritant in U.S.-Russia relations. Such conflicts between an underlying principle of the NPT and the aims of specific countries could become more common in the growth scenario.

The rapid global spread of industrial capacity (such as chemicals, robotic manufacturing) and of new technologies (such as advanced materials, computer-based design and simulation tools, medical isotope separation) will increasingly facilitate proliferation in developing countries that have nuclear weapons ambitions. A fuel cycle infrastructure makes easier both the activity itself and the disguising of this activity. Indeed, even an extensive nuclear fuel cycle RD&D program and associated facilities could open up significant proliferation pathways well before commercial deployment of new technologies.

We conclude that the current non-proliferation regime must be strengthened by both technical and institutional measures with particular attention to the connection between fuel cycle technology and safeguardability. Indeed, if the nonproliferation regime is not strengthened, the option of significant global expansion of nuclear power may be impossible, as various governments react to real or potential threat of nuclear weapons proliferation facilitated by fuel cycle development. The U.S. in particular should recommit itself to strengthening the IAEA and the NPT regime.

The specific technical and institutional measures called for will depend upon the fuel cycle technologies that account for growth in the global growth scenario. We have considered several representative fuel cycles: light water reactors and more advanced thermal reactors and associated fuel forms, operated in an open, once-through fuel cycle; closed cycle with Pu recycling in the PUREX/MOX fuel cycle; and closed fuel cycles based on fast reactors and actinide burning. The priority concern is accounting and control of weapon-usable material during normal operation and detection/prevention of process modification or diversion to produce or acquire such material.[2]

The open fuel cycles seek to avoid the proliferation risk of separated plutonium by requiring that the highly radioactive spent fuel be accounted for until final disposition. This defines the baseline for adequate proliferation-resistance, assuming that spent fuel is emplaced in a geological repository less than a century or so following irradiation (i.e., before the self-protection barrier is lowered excessively). However, the open fuel cycle typically requires enriched uranium fuel, so the spread of enrichment technology remains a concern.

The advanced closed fuel cycles that keep the plutonium associated with some fission products and/or minor actinides also avoid "directly usable" weapons material in normal operation, since there is a chemical separation barrier analogous to that which exists with spent fuel. Nevertheless, closed fuel cycles need strong process safeguards against misuse or diversion. However, the development and eventual deployment of closed fuel cycles in non-nuclear weapons states is a particular risk both from the viewpoint of detecting misuse of fuel cycle facilities, and spreading practical know-how in actinide science and engineering.

Greater proliferation resistance will require the adoption of technical and institutional measures appropriate to the scale and spread of the global growth scenario and responsive to both national and sub-national threats. Proliferation concerns contributed significantly to our conclusion that the open, once-through fuel cycle best meets the global growth scenario objectives, since no fissile material easily usable in a nuclear weapon appears during normal operation, and the "back end" does not have plutonium separation facilities. Enrichment facilities that could be employed for HEU production represent a risk. A variety of measures can minimize the risk: strengthened IAEA technical means to monitor material flows and assays at declared facilities; reliable supply of fresh fuel (and perhaps return of spent fuel) from a relatively small set of suppliers under appropriate safeguards; implementation of IAEA prerogatives with respect to undeclared facilities (the "Additional Protocol"); strengthened export controls on enrichment technologies and associated dual-use technologies; and utilization of national intelligence means and appropriate information sharing with respect to clandestine facility construction and operation. This is a demanding agenda, both diplomatically and in its resource needs, and calls for active effort on the part of the U.S. and other leading nuclear countries. With such an effort, the level of proliferation risk inherent in the possible expansion to 1000 GWe nuclear power by mid-century appears to us to be manageable.

It is clear that international RD&D on closed fuel cycles will continue and indeed grow over the next years, with or without U.S. participation. We believe that such work should be restricted by proliferation considerations to those fuel cycles that do not produce "direct use" nuclear materials in their operation. Current R&D planning discussions in the U.S. reflect this concern. Such fuel cycles may also have manageable proliferation risks when coupled with improved technical and institutional safeguards. However, although advanced closed fuel cycles cannot realistically by deployed for many decades, the R&D program could itself assist and provide cover for proliferants unless structured carefully from the beginning. Today, the international discussions are carried out by those principally interested in developing advanced technologies, without the needed level of engagement from those whose primary responsibility is nonproliferation. The U.S. could play a crucial role in shaping these discussions properly before major efforts are underway.

In this context, the PUREX/MOX fuel cycle is a major issue. It is the current candidate, because of experience, for near-term deployment in nations determined to pursue closed fuel cycles. However, it should be stressed that the PUREX/MOX fuel cycle is not on the "technology pathway" to the advanced fuel cycles discussed earlier (typically, the advanced fuel cycles will involve different separations technology, fuel form, and reactor). The U.S. should work with France, Britain, Russia, Japan, and others to constrain more widespread deployment of this fuel cycle, while recognizing that development of more proliferation-resistant closed fuel cycle technologies is widely viewed as a legitimate aspiration for the distant future. The associated institutional issues encompass examination of the underlying international regime embedded in the NPT/Atoms for Peace framework. All of these issues confront the fundamental question of tradeoffs of national sovereignty in the context of access to nuclear materials and technology. Such issues are intrinsically difficult and time-consuming to resolve through diplomacy, but concomitantly important for realizing the global growth scenario, while preserving international commitment to and confidence in a strong nuclear nonproliferation regime.

In summary, the global growth scenario built primarily upon the once-through thermal reactor fuel cycle would sustain an acceptable level of proliferation resistance if combined with strong safeguards and security measures and timely implementation of long term geological isolation. The PUREX/MOX fuel cycle produces separated plutonium and, given the absence of compelling reasons for its pursuit, should be strongly discouraged in the growth scenario on nonproliferation grounds. Advanced fuel cycles may achieve a reasonable degree of proliferation resistance, but their development needs constant and careful evaluation so as to minimize risk. The somewhat frayed nonproliferation regime will require serious reexamination and strengthening to face the challenge of the global growth scenario, recognizing that fuel cycle-associated proliferation would greatly reduce the attraction of expanded nuclear power as an option for addressing global energy and environmental challenges.

NOTE

1. "DOE's Nonproliferation Programs with Russia, Howard Baker and Lloyd Cutler, co-chairs, Secretary of Energy Advisory Board report, January 2001; "Controlling Nuclear Warheads and Material", M. Bunn, M. Wier, and J. Holdren, Nuclear Threat Initiative report, March 2003.
2. E. Arthur, et. al., "Uranium enrichment technologies: workshop materials," Los Alamos Report — LA-CP-03-0233, (December, 2002).

Chapter 9 — Public Attitudes and Public Understanding

There is little question that the public in the United States and elsewhere is skeptical of nuclear power. A majority of Americans simultaneously approve of the use of nuclear power, but oppose building additional nuclear power plants to meet future energy needs. Since the accident at the Three Mile Island power plant in 1979, 60 percent of the American public has opposed and 35 percent have supported construction of new nuclear power plants, although the intensity of public opposition has lessened in recent years.[1] Large majorities strongly oppose the location of a nuclear power plant within 25 miles of their home.[2] In many European countries, large majorities now oppose the use of nuclear power. Recent Eurobarometer surveys show that 40 percent of Europeans feel that their country should abandon nuclear power because it poses unacceptable risks, compared with 16 percent who feel it is "worthwhile to develop nuclear power."[3]

Why does nuclear power, or for that matter any energy source, receive or lose public confidence? There is a surprising lack of survey data in the public domain that would allow us to understand why people oppose and support specific power sources. [4] To fill that void, we have conducted a survey[5] of 1350 adults in the United States. This internet survey[6] measures public opinion about future use of energy sources, including fossil fuels, nuclear power, hydroelectricity, and solar and wind power.

Our survey showed the same level of skepticism as other surveys. Respondents in our survey, on average, preferred that the United States reduce somewhat nuclear power usage in the future. The same, however, was true of coal, the nation's largest energy source, and oil. On average, respondents wanted to keep natural gas at its current level. And, respondents strongly support a significant expansion of wind and solar power.

On what do these attitudes depend? We explored this question this question two ways. First, we performed a statistical analysis to determine which factors explain who supports nuclear power and who does not. This analysis is presented in the Chapter 9 Appendix. The results are, briefly, as follows:

- Perceived environmental harms weigh most heavily. The average person responded that nuclear power is moderately harmful to the environment, and the difference between someone who perceives nuclear power as "somewhat harmful" and "moderately harmful" is the difference between wanting to expand and wanting to reduce nuclear power in the future.
- Safety and waste are also significant factors. Those who believe that waste can be stored safely for many years express higher levels of support for building additional nuclear power plants. Those who believe that a serious accident is unlikely in the next 10 years also express higher support for nuclear power. The problem is a majority of respondents do not believe that nuclear waste can be stored safely for many years, and the typical respondent believes that a serious reactor accident is somewhat likely in the next 10 years.
- Perceived costs of nuclear power are the third most important factor. Those who

believe nuclear power is uneconomical support it less.

- Surprisingly, concern about global warming, in our survey, does not predict preferences about future use of nuclear power. There is no difference in support for expanding nuclear power between those who are very concerned about global warming and those who are not.
- Political beliefs and demographics, such as age, gender, and income, mattered relatively little, if at all.

Second, we performed an experiment within the survey to measure sensitivity of attitudes to possible changes in cost, waste, and global warming. Half of the sample was provided no information; they are the control group. The remaining half was divided into four groups. These groups were provided with information about future energy prices or about toxic waste from fossil fuels or about global warming or about all three factors (economics, pollution, and global warming). Our aim was not to increase support for nuclear power, but to see how the mix of energy sources would change with accurate information about costs, toxic waste, and global warming.

Only nuclear power showed substantially more support between the control group and the others. Those who received all three pieces of information supported nuclear power and natural gas equally, and supported nuclear power much more than coal and oil.

Information about the relative prices of energy sources produced almost all of this shift. The public perceives solar and wind to be inexpensive. When informed that solar and wind are more expensive than fossil fuels or nuclear power, survey respondents showed substantially less support for expanding solar and wind and substantially more support for nuclear power and somewhat more support for coal and oil. Information about global warming again had no effect on public attitudes toward alternative energy sources.

In our view, these survey data reveal the fundamental importance of the technology itself for public support. American public opinion toward energy is not the product of political ideology or party politics. Rather, public opposition to nuclear power in the United States is due primarily to the public reaction to the concrete problems of the technology and the industry, notably concerns over safety, toxic waste, and poor economics. It is not surprising that the public is skeptical about a technology that has over promised.

Should there be a public campaign to change perceptions about nuclear power? The evidence suggests that such a campaign may have only modest effect. Most of the change would come through education about the high price of alternative energy sources, such as solar and wind. The other possible source of change in public attitudes is the connection between global warming and fossil fuels. The typical person expresses concern about global warming, but that concern does not in turn translate into higher support for carbon free electricity sources, such as nuclear power.

The surer way to cultivate public acceptance of nuclear power, though, is through the improvement of the technology itself and choosing carefully what nuclear technology to use. Developing and deploying technology that proves uneconomical and hazardous will make the global growth scenario infeasible. Technology choices and improvements that lower the cost of nuclear power, that improve waste management and safety, and that lessen any environmental impact will substantially increase support for this power source.

NOTES

1. Eugene A. Rosa & Riley E. Dunlap, "Poll Trends: Nuclear power — three decades of public opinion" Public Opinion Quarterly, *58*, 295-324 (1994). National Science Board, Science and Engineering Indicators 2000, volume 1, page 8–19. Washington DC: National Science Foundation. Survey results vary because researchers ask different questions and in different contexts. Recent surveys range from 60 percent opposed to "building new nuclear power plants" (AP/Washington Post) to 55 percent favoring "new nuclear power plants in the future" (Nuclear Energy Industry tracking survey questionnaire, October 2002, carried out by Bisconti Research Inc). For a discussion of some of these issues and the state of public opinion, see Steve Miller "Pragmatic Concerns Fuel Nuclear Support," IEEE Spectrum, http://www.spectrum.ieee.org/WEBONLY/publicfeature/nov01/natt.html. Because existing survey data do not directly address many of the issues that motivate our inquiry, we conducted our own survey.
2. Associated Press poll conducted by ICR March 12–16 1999, N = 1015 adults nationwide. MIT Energy Survey, June, 2002, N = 1350.
3. European and Energy Matters, 1997, EUROBAROMETER 46.0, Directorate General for Energy, European Commission, February 1997.
4. Studies of particular factors have been conducted. Accidents and waste loom large in public thinking. See, for example, Ellen Peters and Paul Slovic, Journal of Applied Social Psychology, *26*, 1427-1453, (1996). Connie de Boer and Ineke Catsburg, "A Report: The Impact of Nuclear Accidents on Attitudes Toward Nuclear Energy," Public Opinion Quarterly, 52, 254-261 (1988).
5. We surveyed the United States for reasons of cost. A reliable survey of a similar size in another country performed by a reputable survey research firm was too expensive. It is our hope that this survey offers a model for studies of public attitudes toward energy use and development in other countries. The responses might be quite different. For example, Europeans are more concerned with global warming which could influence their attitudes toward nuclear energy.
6. We performed an Internet based survey because of four design advantages over the alternative methods, phone or face-to-face. First, a face-to-face survey was prohibitively costly — at least 10 times the cost of the Internet survey. Second, Internet surveys have much higher response rates than phone surveys. Knowledge Networks, the firm we employed, recruits a pool of approximately 2 million people from which it draws a random sample. Approximately 80 percent of the people sampled responded to our survey within one week. The typical phone survey with a similar cost structure has a non-response rate of around 70 percent. Third, ensuring a higher response rate in a phone survey would have increased costs substantially (approximately double). Fourth, Internet surveys are ideal for the experimental manipulations we performed. We provided information in graphics and text format, which is superior to reading text over the phone.

   The drawback of the Internet survey is that Internet users are not necessarily representative of the population. Knowledge Networks recruits a pool of potential survey respondents from the general population and develops sample weights to allow us to extrapolate to the general population. So, a college educated, high income individual receives less weight than an individual without a bachelor's degree and with modest or low income, because individuals with college educations and above average income are more common in the pool than in the population. Data analyses are performed with appropriate sample weights and controlling for demographic factors.

PART 2

In Chapter 3 we outlined our study approach. We noted that nuclear energy is one important energy option for the future that avoids carbon emission, but that exercising the option for *significant* deployment requires overcoming four challenges — economics, safety, waste, and proliferation. We defined a global growth scenario with a range of future nuclear power deployment between 1000 to 1500 GWe. In Chapter 4, we analyzed three different fuel cycle scenarios and evaluated them against the significant challenges: economics (Chapter 5), safety (Chapter 6), waste management (Chapter 7), and proliferation (Chapter 8). In Chapter 9, we reported on survey results about attitudes of the U.S. public to the technologies we are studying.

This analysis leads us to a conclusion of great significance: the open, once-through fuel cycle best meets the criteria of economic attractiveness and proliferation resistance. Closed fuel cycles may have an advantage from the point of view of long-term waste disposal and, if it ever becomes relevant, resource extension. But closed fuel cycles will be more expensive than once through cycles, until ore resources become very scarce. This is unlikely to happen even with significant growth in nuclear power deployment until the end of this century. We also find that the long-term waste management benefits of separation are outweighed by the short-term risks and costs.

Thus our paramount recommendation is:

For the next decades, government and industry in the United States and elsewhere should give priority to deployment of the once-through fuel cycle, rather than development of the more expensive closed fuel cycle technology involving reprocessing and new advanced thermal or fast reactor technologies.

This recommendation implies a major re-ordering of priorities of the U.S. Department of Energy (DOE) nuclear R&D programs.

The following table indicates how well each of the fuel cycles considered matches the criteria we have used for each of the four objectives:

Fuel Cycle Types and Criteria Ratings

				SAFETY			
	ECONOMICS	WASTE	PROLIFERATION	REACTOR	FUEL CYCLE	REACTOR TYPES	EXAMPLES OF NEW FEATURES
Once through (1)	+	× short term – long term	+	×	+	LWRs CANDU HTGRs	High burn up fuel Thorium Lifetime core Modular Passive safety
Closed thermal (2)	–	– short term + long term	–	×	–	Same plus Molten Salt	
Closed fast (3)	–	– short term + long term	–	**+ to –**	–	Liquid sodium, lead Gas	Advanced PUREX Pyroprocessing Adv partitioning & transmutation Integrated energy parks

+ means relatively advantageous; × means relatively neutral; – means relatively disadvantageous

This table indicates broadly the relative advantage and disadvantage among the different type of fuel cycles. It does not indicate relative standing with respect to other electricity-generating technologies, where the criteria might be quite different (for example, the nonproliferation criterion applies only to nuclear). The economic and waste criteria are likely to be the most crucial for determining nuclear power's future.

We have not found and, based on current knowledge, do not believe it is realistic to expect that there are new reactor and fuel cycle technologies that simultaneously overcome the problems of cost, safety, waste, and proliferation.

In this second part of our report we present recommendations enabling a path that leads from today to the mid-century scenario. We do not establish a timetable or specific goals. Rather our purpose is to identify measures — both technical and institutional – that address the major barriers to nuclear power expansion. We present our recommendations in three chapters: Chapter 10, which addresses economic incentives; Chapter 11, which addresses measures bearing on waste management, safety, and proliferation; and Chapter 12, which presents a recommended government R&D program.

Chapter 10 — Recommended Measures to Resolve Uncertainties about the Economics of Nuclear Power

The analysis of Chapter 5 concludes that at the present time nuclear power is widely perceived by potential investors to be more costly than coal and gas alternatives. While segments of the nuclear industry argue that nuclear plants could be built much more cheaply than is widely perceived, investors in what has become a competitive electricity market in many countries do not believe this is so. Chapter 5 also discusses what must happen for nuclear energy to be competitive with these electricity supply alternatives: credible significant reduction in the perceived level and uncertainty associated with capital and operation and maintenance (O&M) costs of new nuclear plants; resolution of regulatory uncertainties regarding siting, construction time to completion, and costly redesign requirements; higher real acquisition cost for natural gas; and a significant value placed on the reduction in carbon emissions resulting from displacement of fossil-generation resources with nuclear power.[1] In this section we address what measures the government should take to improve nuclear power economics.

We note that a variety of reasons are put forward to justify government support for energy supply and energy efficiency technologies. They all reflect an argument that one or more social costs or benefits associated with the use of a particular technology are not properly reflected in investor and consumer decisions. Thus policies are designed, directly or indirectly, to internalize these social costs and benefits or to compensate for market imperfections more generally. Externalities that are considered include:

- internalizing costs of threats to national security;
- internalizing social benefits of favorable learning curve effects;
- compensating for the costs of regulatory uncertainty that may confront and be resolved by "first movers" in a regulatory process;
- internalizing the benefits of R&D spillovers that accrue to society at large but cannot be fully captured by investors in R&D;
- correcting other market imperfections, including imperfect information, capital market imperfections, and other decision making imperfections;
- internalizing costs of damages to the environment.

These are arguments for government support that are not unique to nuclear power and indeed are marshaled by advocates of many energy technologies, in order to justify government subsidies of one kind or another. The result is that at one extreme, skeptics argue the government should do nothing to support technologies, and at the other extreme, enthusiasts argue the government should manage key aspects of the innovation process. Indeed there is nothing in theory or experience to suggest that, in general, the government is better able to manage technical development in a manner that leads to its wide adoption in the private sector. Credible arguments for government support for R&D all turn on compensating for some type of market failure that leads to underinvestment in the particular technologies at issue. Government actions should be carefully targeted to a clearly defined market failure. In addition, questions of how much money should be spent, how it should be spent, and when it should be spent must all reflect well defined goals that permit measurement of progress.

Nor is the government in a better position than the private sector to judge the future price and availability of fuels. On the other hand, the consequences of *rapidly changing* higher (or lower) than expected fuel prices may be different for the private sector than for the government. If natural gas prices move sharply higher than expected, individual firms will be winners or losers, but the government, as a practical matter, will be called upon to take measures to compensate for significant adverse economic impacts resulting from these higher prices.

Massive research, development, and demonstrations of nuclear power projects were supported by the Department of Energy (DOE) and predecessor agencies in the 1960s and 1970s. These projects advanced costly new technologies too rapidly, e.g. commercial reprocessing and liquid metal fast breeder reactors. They misestimated the cost of electricity from first generation light water reactors; they paid insufficient attention to the critical issues of safety, waste management, and proliferation that have proven to be of concern to the public. Ironically, the lessons of the unintended bad consequences of past government involvement in the nuclear industry are contradictory: first, the government bears some responsibility for reviving this important energy option, but second, we should advance new proposals for government support with special clarity about their purpose and realistic expectations about success.

Our position is that the prospect of global climate change from greenhouse gas emissions and the adverse consequences that flow from these emissions is the principal justification for government support of the nuclear energy option. The environmental externality of carbon dioxide (CO_2) emissions means that price of carbon based fuel and electricity produced from it are too low. In an ideal world, this externality would be internalized either with a carbon tax or an emissions cap and trade program[2]. A carbon tax places a price on carbon emissions directly. A cap and trade program would establish a national CO_2 emissions cap, issue tradeable emissions permits equal to the cap, and require all emissions sources (at an appropriate place in the vertical chain from fossil fuel production to fossil fuel use) to hold permits to cover their emissions. The market price for these emissions permits then defines the price for CO_2, in much the same way as would a tax. Hybrid programs (e.g., cap and trade with an elastic supply of permits at a specified price) are also feasible and under consideration.

In practice we are unlikely to see the United States adopt any carbon emissions tax; proposing energy taxes, or what appear to be like energy taxes, has not proven to be career enhancing for elected officials. An essentially equivalent "cap and trade" policy that has proven successful in minimizing the social cost of reducing SO_2 emissions produced from coal-fired power plants is uncertain, at least in the near term, although legislation has been proposed for such a program. Instead we are likely to continue to see "second best" surrogate measures designed to reduce CO_2 emissions from power generation. These measures will include renewable energy portfolio standards, tax credits and production subsidies for a range of renewable energy supply and conservation technologies, and direct federal support for energy supply and conservation R&D programs. At the present time, nuclear power has generally been excluded from these programs and this undermines its ability to compete fairly to provide carbon-free electricity.

Our first principle is that all external costs associated with each electricity generating technology should be included in the price of electricity. For carbon emissions this means that all options for reducing carbon emissions should be treated equally. We should seek to lower carbon emissions at the lowest overall social cost and not adopt arbitrary rules for which technologies are 'in' and which technologies are ‘out’ of consideration for achieving lower emissions. The energy bill almost passed by Congress in the fall of 2002 contained a renewable energy portfolio standard mandating the use of specified percentages of renewable energy technologies by all retail electricity suppliers. Several states have already adopted similar renewable energy portfolio standards. The existing and proposed portfolio standards do not include incremental nuclear power as an alternative qualifying supply technology. *We recommend that incremental nuclear power be eligible for all “carbon free” federal portfolio standards programs.* Specifically, if tax or production credits are extended to a renewable technology, such as wind, photovoltaics, hydropower, and geothermal because they do not produce CO_2 in conjunction with the production of electricity, then incremental nuclear energy should be included.

It follows that the external costs unique to nuclear energy – notably waste disposal, safety, and proliferation resistance – should also be internalized in the cost and price of nuclear energy. The already established federally mandated nuclear waste disposal fee for nuclear power is a proper step in this direction, as are the costs of security needed to meet Nuclear Regulatory Commission requirements.

Our principal justification for federal action is avoiding the external cost of CO_2 emission. We also see merit in other arguments for federal intervention, but we are mindful of the need to craft measures that least distort private market forces, do not offer perverse incentives to industry, and conserve taxpayer dollars. For example, we are impressed by the widespread perception that uncertain regulation – affecting both licensing and siting of nuclear plants – is a major barrier to investment. There are two effects: a direct effect of lengthening project construction time due to the unpredictable time required to obtain regulatory approval, and the indirect effect of concern about the possibility of the retroactive application of a regulatory standard after a project has been launched. Regulation always creates uncertainty for investors. But the first to pass through the regulatory process will establish “learning by doing.” First movers will effectively develop a set of new regulatory procedures that will then be applicable to follow-on applicants. Thus, the first movers incur costs but create benefits for others that they cannot (necessarily) capture.

The federal government cannot remove all the regulatory uncertainty, and indeed, other major energy facilities e.g. coal plants, electrical transmission lines, LNG terminals, face similar regulatory uncertainty. But, the government should take action to reduce this regulatory uncertainty as much as possible, without introducing perverse incentives for nuclear power and other energy facilities.

GOVERNMENT ACTIONS

We recommend three government actions. First, the government can review existing federal regulations to assure that the procedures in place, primarily at the NRC, but at other regulatory agencies as well (EPA and DOT), strike the correct balance between protecting the public interest and encouraging commerce. The Nuclear Regulatory certification of generic nuclear plant designs and adoption of a procedure for granting combined construction and operating licenses (COL) is a step in the right direction. *We believe that consideration should be given to the federal government paying a portion of the administrative costs for:*

1. *site banking for an envelope of plants*, i.e. obtaining approval for sites that might be used for construction of new plants. (In many cases the site for prospective new units will be at the location of existing plants);
2. *certifying a new plant design by the NRC.* Currently the Westinghouse AP600 and the GE System 80 advanced boiling water reactors are certified. Limited government financial assistance for certification of the Westinghouse AP1000, an HTGR design, and the Heavy Water Reactor (HWR) designed by the Atomic Energy of Canada (AECL) would

add valuable options to those considering relatively near term deployment of nuclear plants;

3. *sharing in the costs of applying for a COL license at the NRC*, in circumstances when the license would be used or banked.

The size of government subvention in each instance could be less than $20 million and 10-15 projects over a number of years would go a long way to reducing some of the outstanding uncertainty with regard to early deployment of nuclear power in the United States.

The next stage of government involvement might be sharing of some of the costs of one or more commercial demonstration projects. We distinguish between two types of "demonstration" projects. The first, and most common, type is the government sharing the costs of demonstrating a new technology in terms of its technical performance, environmental impacts, and cost. Examples include past DOE efforts to demonstrate synthetic fuel technologies, to encourage liquid metal fast breeder reactors, advanced photovoltaic and large wind energy systems. Candidate nuclear technology demonstration projects of this type might be demonstrating pyroprocessing technology or developing a modular High Temperature Gas Cooled reactor. For nuclear power, each technology demonstration of this type is likely to cost in excess of $1 billion. *We do not recommend that the government undertake any such large scale demonstration project of this type at the present time*. Such projects might be justified in the future, when it becomes clear that there is a need and economic basis for moving to alternative systems or, eventually, to a closed fuel cycle.

The second type of "demonstration" project is a first nuclear project carried out by industry, whose success would demonstrate to other private generators that the risks associated with nuclear power are manageable and the cost of new nuclear power is acceptable. Evidently, this type of demonstration is credible only if the government is *not* involved in design and construction or involved in an indirect manner. Otherwise the project has no "demonstration" value to practical investors considering future investments. The purpose of this demonstration is not to demonstrate a new technology but rather to demonstrate the cost of practical realization of a technology selected by private investors.

But a first project bears a risk that subsequent projects do not bear. Investors in subsequent projects have the knowledge that the first of a kind project has been successful (in which case they proceed with greater confidence) or that it has failed (in which case they do not proceed).[3] Yet, if the plant successfully meets its cost targets, a large number of additional plants will be built by the industry, taking advantage of the resolution of risk accomplished by the first project were it to proceed.

The initial project backers cannot capture the value of the information they provide to subsequent projects. Clearly there is a value to going second and a rational reason to share the risk of the first plant among an entire industry. Such sharing of risk is a matter of bargaining and difficult to achieve in practice. So it may well be in the government's interest to step in to assure that the demonstration occurs and the uncertainty is resolved. Given the circumstances of nuclear power today, this government interest in the demonstration of actual cost is justified, even when the technology selected is known and plants have been built in the past (although at a cost that today would be considered unaffordable). There must, of course, be a credible basis for believing that technology and industry practices have changed so that a lower capital cost outcome is a reasonable possibility. If the demonstration project results are to be credible to the private sector, the government's involvement must not be intrusive.

We believe the government should step in and increase the likelihood of practical demonstration of nuclear power by providing financial incentive to first movers.[4] We propose a production tax credit of up to $200 per kWe of the construction cost of up to ten "first mover" plants. This benefit might be paid out at 1.7 cents per kWe-hr, over a year and a half of full-power plant operation, since the annual value of this production credit for a 1000 MWe plant operating at 90% capacity factor is $134 million. The $200 per kWe government subsidy would provide $200 million for a 1000 MWe nuclear plant, about 10% of the historically-based total construction cost estimate; accordingly the total outlay for the program could be up to $2 billion paid out over several years.

We prefer the production tax credit mechanism because it offers the greatest incentives for projects to be completed and because it can be extended to other carbon free electricity technologies, for example renewables (such as wind which currently enjoys a 1.7 cents per kWe-hr tax credit for ten years) and coal with carbon capture and sequestration. The credit of 1.7 cents per kWe-hr is equivalent to a credit of $70 per avoided metric ton of carbon if the electricity were to come from coal plants, (or $160 from natural gas plants). Of course the carbon emission reduction would continue after the public assistance ended for the plant life (perhaps 60 years for nuclear). Even with this "first mover" incentive, private industry may not choose to proceed with new nuclear plant investment until some carbon free benefit is firmly established. If no new nuclear plant is built, the government will not pay any subsidy and the production tax credit will remain available as an incentive to future investment decisions.

These actions address regulatory and startup-cost issues identified by the nuclear industry as barriers to moving forward with a new generation of commercial nuclear plants. The actions will be effective in stimulating additional investments in nuclear generating capacity only if the industry can live up to its own expectations of being able to reduce considerably overnight capital costs for new plants far below historical experience. With these barriers removed, it is then up to the industry to demonstrate through its own investments in new nuclear power plants, that its cost projections can in fact be realized in practice, and that nuclear power can be competitive with fossil-fuel and renewable energy alternatives.

The government should also continue a vigorous R&D program for nuclear energy. In this section we are focused on the measures the government should take to lower the cost of nuclear power. An R&D effort focused on lowering the capital cost and the O&M cost of nuclear power is also important. But the nuclear R&D effort should also address a range of other matters: proliferation resistance, waste management, and fuel cycle research. The recommended R&D program is addressed in Chapter 12.

PRICE-ANDERSON INSURANCE

Originally enacted in 1957, the Price-Anderson Act establishes a framework defining the terms and conditions of payments to the public for damages caused by a nuclear accident. The Act has been amended several times, with the most recent major changes reflected in the 1988 amendments.[5] The act covers nuclear power plants, other nuclear facilities, and DOE contractors working on nuclear energy projects. The Act does not provide payments for the costs of any damages to a nuclear facility caused by an accident. We focus here on the provisions for nuclear power plants.

The Act requires that nuclear power plant licensees must purchase the maximum amount of commercial liability insurance available in the private market at a reasonable price. This is currently $200 million per plant. In addition, all nuclear power plant licensees must participate in what is effectively a joint-insurance pool. In the case of a nuclear accident whose costs exceed the first layer of private insurance coverage, each nuclear plant is obligated to make payments of up to $88 million[6] to cover any additional costs up to about $9.3 billion at the present time. The compensation provision of both the first and the second layers of insurance are "no fault" and not subject to civil liability litigation. If the cost of a nuclear accident exceeds

$9.5 billion, there are no further financial obligations placed on the nuclear plant owners. Since the Price-Anderson Act went into effect, $202 million has been paid in claims, all of it from the nuclear insurance pools. The largest single claim was $70 million in connection with the Three Mile Island accident.

Perhaps the most controversial aspect of Price Anderson is the current $9.5 billion limit on the civil liability of a licensee where the accident has occurred. Critics argue that this represents a significant subsidy to nuclear power. Estimates vary from about $3.5 million per plant per year to $30 million per plant per year ($2001). Critics of Price- Anderson often cite a 1990 study by economists Jeffrey Dubin and Geoffrey Rothwell that estimated the cost of the subsidy at about $30 million per year per plant or over $3 billion per year for the entire industry.[7] However, these calculations contain several errors that are now widely recognized, except perhaps by those who find it convenient to argue that Price Anderson represents a large subsidy. Heyes and Liston-Heyes show that errors in the original calculation reduce the level of the "subsidy" by a factor of between four and ten.[8] A subsequent paper by Rothwell argues that further corrections would reduce the value of the subsidy by as much as a factor of one million.[9] The correct value of the "subsidy" that would arise from the appropriate application of these methods is very small.

There have been arguments about whether Price-Anderson is or is not a "subsidy" to nuclear power. In some sense it is a subsidy, since it places a current $9.5 billion limit on the private liability payment obligations of nuclear plant licensees. Damages in excess of $9.5 billion would be absorbed by some combination of federal, state and local governments and by the individuals and businesses suffering damages from the accident. However, it is not at all obvious that this is the proper comparison. There is no obligation placed on businesses to carry full insurance against damages caused by an accident. Indeed, full insurance would be quite unusual. While a business would still be liable for damages in excess of its insurance coverage, any corporation effectively has limited liability, since a very large accident could exceed the financial resources of the company, and it would seek protection under the bankruptcy laws. So, for example, the collapse of a dam or the explosion of an oil tanker could cause substantial damages and these damages could exceed both the firm's liability insurance coverage and the value of the equity in the business. U.S. law does **not** require firms generally to carry any liability insurance, and the limited liability corporation places a limit on the damages that any company would pay as a result of an accident.

From this perspective, Price Anderson *requires* nuclear power plant licensees to carry substantial amounts of insurance coverage to provide compensation to the public in the case of a nuclear accident. It creates a second layer of pooled insurance coverage over and above what is available in the private market, and this insurance pool is feasible only because all licensees are required to participate in it. Moreover, the $9.5 billion coverage limit exceeds the equity values of many companies that operate nuclear power plants. Absent Price-Anderson, nuclear plant owners could decide to carry much less insurance and default to bankruptcy protection in the case of a catastrophic accident. In the end, if there were a catastrophic accident, the Price-Anderson framework may very well cost the government and damaged parties less than would be the case without it.

This being said, we would have no objection to assessing a fee to nuclear plants for the expected fair actuarial value of this third layer of insurance coverage. The estimates appear to suggest a cost of no higher than about $3 million per year per plant.

We have suggested five different roles for the federal government in promoting nuclear energy; these are:

1. assuring that nuclear energy is considered on the same basis as other technologies that reduce carbon emissions;
2. taking steps to reduce regulatory uncertainty;
3. providing partial support for industry projects that demonstrates the economic competitiveness of nuclear energy;
4. nuclear technology R&D;
5. reauthorizing Price-Andersen nuclear accident insurance.

This package of government actions is appropriate for nuclear technology in its present circumstances. We stress that our intention is not to advocate support for nuclear power at the expense of the other major alternatives — renewable energy, carbon sequestration, energy efficiency — that also can reduce greenhouse gas emissions. Of course the appropriate package of government incentives for each alternative must be tailored to the particular circumstance of that technology. In order to be confident that at least one option emerges as an attractive economic choice, the federal government should support programs on all these alternatives.

NOTES

1. We modeled this as a carbon tax in Chapter 5 to show how alternative carbon emissions valuations would affect the relative *social value* of nuclear power. However, a variety of other policies (e.g., cap and trade) might be used to internalize the social cost of carbon emissions.

2. A.D. Ellerman, P.L. Joskow, and D.A. Harrison, *Emissions Trading in the United States*, Pew Center for Global Climate Change, May 2003.

3. The large uncertain capital cost of a first plant is a critical barrier to nuclear power. This uncertainty is one aspect of "first mover" costs. A simple example illustrates the justification for government action. Assume that there is a probability p that the first plant will have a $1500/KWe overnight cost and a probability (1-p) that the plant will have an overnight capital cost of $2500/kWe,

   Expected capital cost per kWe = $1500p +$2500(1-p).

   For a realistic probability p, a prospective investor may judge the expected cost of the first plant to be too large to justify proceeding. If the government pays a portion of the difference between the two outcomes , (in this case $1000/kWe), an initial plant will be built and all future investors will have the benefit of knowing the answer — either the plant cost $1500/kWe and many plants will follow, or the plant costs $2500/kWe and no additional plants will be built.

4. It might be argued that with about 350 GWe of nuclear generating capacity world wide that the "first- time" costs are behind us. However, given the long hiatus in construction of new nuclear plants, the retirement of significant infrastructure needed to restart the program, the lack of experience with new licensing regulations, and the planned use of new reactor designs and construction management techniques, it is appropriate to think of a future program as having many of the characteristics of a new program. We have been building (and subsidizing) the construction of wind generating technologies for 25 years and prospects for "moving down the learning curve" still are used to justify continuing subsidies and other valuable preference for wind generation.

5. The provisions of the Act were extended to December 31, 2003 in the consolidated appropriations bill passed by Congress and signed by the President in early 2003. A longer extension is included in the House and Senate energy bills now being considered in Congress.

6. As of 2002. The value of this obligation is indexed to inflation.

7. J.A. Dubin and G.S. Rothwell, "Subsidy to Nuclear Power Through Price-Anderson Liability Limit," *Contemporary Policy Issues,* p 3, 7 (1990).

8. A. Heyes and C. Liston-Heyes, "Subsidy for Nuclear Power Through the Price-Anderson Liability Limit," *Contemporary Economic Policy*, January 1998, pp. 122-124.

9. Geoffrey Rothwell, "Further Comments on Subsidy to Nuclear Power through the Price Anderson Liability Limit," mimeo, August 2001.

Chapter 11 — Recommendations Bearing on Safety, Waste Management, and Proliferation

SAFETY

Our study has not been able to address each aspect of concern as thoroughly as deserved. One example is safety of nuclear operations. Accordingly, we report here views of our group that we believe to be sound but that are not supported by adequate analysis. We have four observations to make about the safety of nuclear operations:

- Public and governmental attention is understandably focused on reactor accidents because of Three Mile Island and Chernoybl. But all aspects of the nuclear fuel cycle present safety risks, as with other major industrial enterprises, and these risks need to be assessed in an objective and quantitative fashion, in order to establish standards for design, construction, and operations.
- There is an important body of informed technical opinion that believes a nuclear reactor technology can be made with negligible possibility of a severe reactor accident. HTGR reactors are often put forward as an example, because of the very large heat capacity of the power plant and the fuel design.
- Reactor safety depends on a strong safety culture involving management and the entire work force.
- The implied level of risk of serious nuclear accidents based on the existing level of worldwide deployment and number of serious accidents (2) that have been experienced is about 1 accident per 10^4 reactor-years of operation. If nuclear power is to expand to the mid-century benchmark of our global growth scenario, and if we assume the public's tolerance for nuclear accidents is unchanged, then the safety level that must be met should progressively improve by about one order of magnitude to 1 accident per 10^5 reactor-years. Advanced light water reactors are believed to achieve this improvement.
- We have given some thought but reached no conclusion about the regulatory regime that provides the best incentive for safe operation of the nuclear enterprise. The U.S. Nuclear Regulatory Commission (NRC) regime is based on prescriptive regulation, accompanied by inspection and enforcement of rules administered by an independent regulatory commission governed by strict procedural rules. Moreover the NRC is asked to address more than issues of safety, for example proliferation and antitrust concerns. This is not the only regulatory model that can be imagined. Indeed, the Environmental Protection Agency and Federal Aviation Administration each present a very different regulatory approach.

Aside from technical safety considerations, the NRC procedures offer a very important opportunity for public involvement in the decision making process that leads to the decision to operate a nuclear plant. If a different regulatory process is adopted the interveners who seek a voice in the decision will not go away. They will demand, and legitimately so, another avenue to make their views known. So changing the rules for safety decisions should not be used as a device for stifling the legitimate expression of different views about the benefits and costs of nuclear power.

In sum, redesign of the nuclear safety regime must address two separate and important concerns: assuring safety and providing opportunity for public involvement.

We recommend: *The government should, as part of its near-term R&D program, develop more fully the capabilities to analyze life-cycle health and safety impacts of fuel cycle facilities and focus reactor development on options that can achieve enhanced safety standards and are deployable within a couple of decades*. We propose $50 million per year for this purpose.

WASTE MANAGEMENT

The management and disposal of high-level radioactive waste continues to be one of the primary obstacles to the development of the nuclear power industry around the world. We concur with the many independent expert reviews that have concluded that the geologic disposal approach is capable of safely isolating the waste from the biosphere for as long as it poses significant risks. Successful implementation of this approach has yet to be demonstrated, however. Within the next 10-20 years, it is likely that one or two full-scale high-level waste repositories will be commissioned in the United States and elsewhere. Public opposition will continue to be a major obstacle to repository siting in many countries, however, and progress towards establishing operating repositories will be slow.

For fifteen years, the scientific and technical focus of the U.S. high-level waste management program has been directed almost exclusively on the investigation and development of the Yucca Mountain site. The focus on Yucca Mountain will continue as design and licensing activities gain momentum over the next few years. The successful commissioning and operation of Yucca Mountain would be a significant step towards the secure disposal of nuclear waste. However, a broader focus for the U.S. nuclear waste program is needed to provide a foundation for a possible expansion of the nuclear power industry in the U.S. and overseas.

Our assessment of advanced technical strategies for waste management and disposal in Chapter 7 led to the following key conclusions:

- Replacing the current ad hoc approach to spent fuel storage with an explicit strategy to store spent fuel for a period of several decades, prior to reprocessing and/or geologic disposal, will create additional flexibility and robustness in the waste management system and, if organized internationally, can also provide significant non-proliferation benefits.
- We do not believe that a convincing case can be made, on the basis of waste management considerations alone, that advanced fuel cycle schemes featuring waste partitioning and transmutation will yield long-term benefits that outweigh the attendant short term risks and costs.

  We recognize that future technology developments could change the balance of costs, risks, and benefits. But for our basic conclusion to change, not only would the expected long term risks from geologic repositories have to be significantly higher than those indicated in current risk assessments, but the incremental costs and short-term safety and environmental risks would have to be greatly reduced relative to current expectations and experience.
- Technical modifications to waste management strategies in the once-through fuel cycle are potentially available that could yield benefits at least as great as those claimed for advanced fuel cycles featuring waste partitioning and transmutation, and with fewer short-term risks and lower costs of development and deployment.

In light of these conclusions, we believe that the following actions would both benefit current waste management efforts and help to lay the foundation for a possible future expansion of the nuclear power industry. *First, the U.S.*

Department of Energy should augment its current focus on Yucca Mountain with a balanced, long-term waste management R&D program. The broad goals of this program should be to investigate and develop waste management and disposal technologies that would offer improved short and/or long term performance. The program should encompass a balanced portfolio of technologies, including both incremental improvements to the current mainstream approach and more far-reaching innovations. *The program should include the characterization and investigation of alternative engineered barriers and geochemical and hydrological environments for waste repositories, as well as alternatives to the repository concept itself.*

Among alternatives to mined repositories, the deep borehole disposal approach has the potential to reduce significantly the already low risk of long-term radiation exposure and merits a significant research and development program, with the goal of determining operational, safety, and regulatory viability within a decade. This program should investigate methods for detailed site characterization at depth, mechanisms for possible radionuclide transport to the surface, alternative approaches to monitoring and retrieval of emplaced material, plugging and sealing techniques, site suitability criteria, and overall system optimization. Parallel investigations by regulatory and standard-setting bodies should also be undertaken.

The DOE high-level waste R&D program should be separated organizationally from waste management operations. A clear organizational separation will be necessary to resist pressures to narrow the scope of the R&D program. A stable source of funding will also be essential to the success of the R&D program.

The tenth of a cent per kilowatt hour waste management fee should be re-evaluated with a view to creating economic incentives for waste generators and others to develop and implement technologies that would reduce the risks and/or costs of waste disposal while ensuring the financial viability of the overall waste management program.

A period of many decades of interim spent fuel storage should be incorporated into the design of the waste management system as an integral part of the system architecture. A network of centralized facilities for storing spent fuel for several decades should be established in the U.S. and internationally.

The U.S. should actively pursue closer international coordination of standards and regulations for waste transportation, storage and disposal.

PROLIFERATION

The nonproliferation concerns associated with the global growth scenario discussed in Chapter 8 call for an international response that:

- ☐ strengthens the institutional underpinnings of the safeguards regime now, preparatory to a period of expanded nuclear power deployment; and
- ☐ guides nuclear fuel cycle development in ways that reinforce shared nonproliferation objectives.

Strengthening international norms for fuel cycle fissile material security and facility monitoring

The IAEA, functioning under the United Nations, is the key organization for implementing the international safeguards regime among NPT signatories. It also has the role of promoter of peaceful uses of atomic energy. The IAEA has built a foundation of bilateral safeguards agreements that, in effect, codify a compromise between national sovereignty, with respect to fuel cycle facility reporting and inspection, in the interests of an international regime that diminishes the threat of nuclear proliferation and provides access to civilian nuclear technology. Several steps to strengthen this regime should be pursued promptly:

1. *The IAEA should focus overwhelmingly on safety and safeguards,* for which it is uniquely positioned by reason of its bilateral agreements and U.N. affiliation. This is consistent with the spirit of separating regulatory/security functions and nuclear power development, as has been done in the United States and many other countries. The process already initiated for strengthening physical protection standards needs to be accelerated.

   Inspection resources should be allocated by a risk-based approach and in turn, the industrialized nations should increase their financial support for the safeguards function.

   The U.N. Security Council should develop guidelines for multilateral sanctions in the event of serious violations of safeguards agreements.

2. *The IAEA needs the authority to carry out inspections beyond declared facilities,* spurred by information developed by or reported to the agency. The restriction of inspections to declared facilities will undermine confidence in the global growth scenario. Thus, the Additional Protocol of the IAEA needs to be implemented uniformly across non-weapons states.

3. *Greater attention should be placed on the proliferation risks of the front end of the fuel cycle.* While we have emphasized the back end of the fuel cycle as a potential source of weapons-usable plutonium, the front end also deserves attention, especially in the context of undeclared facilities. Clandestine uranium enrichment programs, as have appeared in Iraq, Iran, North Korea and elsewhere, may present a dramatically increasing threat. Uneconomic technologies may in some cases be utilized for "batch scale" enrichment sufficient to produce HEU for a small number of nuclear weapons.

   For commercial scale enrichment, the economic choice today lies with centrifuges. Centrifuge design information was not adequately controlled in the past, so further diffusion of the technology requires tracking and transfer constraints on the specialized materials and components used to build centrifuges. This has proved to be difficult. There are also nonproliferation risks associated with both older technologies (gaseous diffusion, electromagnetic separators) that have been used on a significant scale and newer technologies (laser separation, chemical exchange) that have not yet gone beyond bench/prototype scale. Some of these technologies have very small "footprints" for tracking, detection, and control and may rely on many increasingly ubiquitous dual-use technologies.

   A concerted effort should be devoted to ongoing evaluation of isotope separation technologies, development of associated control mechanisms, and appropriate information sharing with the IAEA. Specifically the U.S. and other industrialized nations should strengthen intelligence collection and dual-use export control regimes with respect to isotope separation technology.

4. The IAEA safeguards framework should move from an approach based on accounting/reporting and periodic inspection to an approach based on continuous surveillance/-containment/security. This is crucial for PUREX/MOX fuel cycle facilities. For example, the Rokkasho PUREX plant nearing completion in Japan will process 800 tonnes of material annually, separating plutonium in amounts where accounting uncertainties will easily exceed a significant quantity (8 kg). An effective safeguard system should be integrated in the plant and process design, with a "real time" measurement/communications system. This system should be benchmarked by use of modeling/simulation for the process flows. Such a safeguards paradigm goes well beyond that currently followed by the agency, including the requirement for extensive information sharing.

   Additional important measures needed to safeguard the fuel cycle are highlighted by the PUREX/MOX case. Secure transportation of separated plutonium from separations to fuel fabrication plants is a concern to all nations, irrespective of the transportation route. A design basis threat, appropriate to the increasing capabilities of terrorist or criminal organizations with international reach, needs to be adopted and reliably implemented (this is currently only recommended by the IAEA). A broader set of IAEA standards for physical protection, associated with appropriate inspections, should be institutionalized and become part of an enforcement mandate.

Facilities should be co-located to eliminate vulnerable transportation links and to reduce separated plutonium inventories to the minimum needed for fuel cycle operation. The accumulated Pu inventory of 200 tonnes should be recognized as an important shortcoming of current fuel cycle operation, and reduction to minimum working inventories should be a near term priority, including for the weapons states.

Internationally supervised, integrated fuel cycle facilities are amenable to implementation of continuous surveillance/containment/security and should be encouraged where appropriate. In the near term, creation of international spent fuel storage facilities should be pursued, with no reprocessing allowed, at least until final disposition is resolved. For the longer term, internationally monitored fuel cycle centers could be the locus for advanced actinide recycling, should it prove attractive.

Fuel cycle analysis, research, development, and demonstration (ARD&D) must characterize and explore measures to minimize proliferation risks

Our global growth scenario envisions an open fuel cycle architecture at least until mid-century, with the advanced closed fuel cycles possibly deployed later and then only if significant improvements can be demonstrated. The principal driver for this conclusion is the clear economic advantage of the open fuel cycle, with proliferation resistance an important additional feature.

The PUREX/MOX fuel cycle remains a particularly poor choice since it costs more, produces weapons-usable separated plutonium in normal operations, and has unimpressive benefits with respect to uranium resource extension (for at least fifty years) and waste management. Nevertheless, several countries have made a substantial commitment to this fuel cycle over the past quarter century. Accordingly, advanced fuel cycle development will continue to be of interest to a number of countries and a subject of discussion for international collaboration.

The ARD&D program advanced later in Chapter 12 takes into account the need to reduce proliferation risks at every stage of the growth and evolution of nuclear power around the world. International analysis and research on advanced fuel cycles should focus only on technology pathways that do not produce weapons usable material during operation (for example, by leaving some uranium, fission products and/or minor actinides with the recycled plutonium, which in turn can achieve very high burnup to degrade the plutonium isotopics).

There are advanced fuel cycle combinations of reactor, fuel form, and separations technology that satisfy these conditions and, with appropriate stringent institutional arrangements, can have significantly better proliferation resistance than the PUREX/MOX fuel cycle – and perhaps approaching that of the open fuel cycle. In that light, the PUREX/MOX fuel cycle should be recognized as not being on the technology pathway to such advanced fuel cycles, and thus not a focus for further development or deployment.

The United States is engaged in the still relatively early stages of an international collaboration, called the Generation IV Forum, mapping out an R&D agenda for advanced reactors and perhaps, eventually, fuel cycles. The nuclear nonproliferation offices in the Department of Energy, Department of State, and National Security Council should play a much more active role along with the DOE Office of Nuclear Energy, Science, and Technology in guiding U.S. participation and leadership in Generation IV and especially in an international advanced fuel cycle initiative. We stress that such collaborative R&D can inadvertently facilitate proliferation through transfer of know-how and requirements for new nuclear infrastructure.

The recommendations put forward on nonproliferation represent a considerable change in the way of "doing business" under the NPT regime. The underlying basis of the NPT/Atoms for Peace framework and treaty structure is to permit all countries to have access to nuclear electricity production benefits and to support nuclear technologies, while implementing IAEA safeguards agreements to avoid the proliferation risk of supporting fuel cycle facilities (both enrichment and reprocessing) that can produce weapons-usable material. Commercial nuclear reactors are not intrinsically a proliferation risk.

We suggest a new approach that retains this framework and is based on technical assessment of risk, but politically non-discriminatory. This approach centers on classifying states as "privileged" of nuclear reactors or as "fuel cycle states." Declared "privileged states" would operate nuclear reactors according to their internal economic decisions about nuclear power versus alternatives, with international support for reactor construction, operational training and technical assistance, lifetime fresh fuel, and removal of spent fuel. Privileged states would not be eligible for fuel cycle assistance (enrichment, fuel fabrication, reprocessing). Thus "privileged" states would be low risk for proliferation and would gain several benefits: absence of intrusive safeguards and inspections, relief from expensive fuel cycle infrastructure development costs, and in particular elimination of nuclear spent fuel/waste management challenges. This approach is feasible under our global growth scenario — for example, in the balanced fast reactor/closed fuel cycle analyzed in Chapter 4, 55% of the reactors are once-through thermal reactors suitable for deployment in "privileged" states with their spent fuel sent to "fuel cycle" states for separation and transmutation. On the other hand, the "fuel cycle states" would be subject to a new level of safeguards and security requirements, along the line of those recommended above. Both groups of states would be subject to the Additional Protocol with respect to undeclared facilities. Such an arrangement is a technology- and risk-based approach in the spirit of Article IV of the NPT, offering considerable benefits for those who restrict their nuclear activities while benefiting from nuclear power[1]. In addition, a stringent sanctions regime under the United Nations Security Council would be put in place for violations of the nonproliferation regime, and more stringent restrictions placed on those who choose to be outside the framework.

Clearly this new risk based approach is one that would take many years to formulate in detail and negotiate. Its very difficulty — an enhanced safeguards regime, international spent fuel management, stringent sanctions — highlights its importance for the global growth scenario. The new approach is most easily advanced while the once-through fuel cycle dominates and before nuclear power experiences dramatic growth in capacity and in geographical distribution.

A strengthened nonproliferation regime is a necessary condition for responsibly expanding nuclear power globally on a significant scale. *We recommend the U.S. government actively pursue the technical risk based approach to strengthening the non-proliferation regime outlined above.*

NOTE

1. Many of these elements (fresh fuel supply, spent fuel return, reactor construction assistance, Additional Protocol) have been discussed intensively over several years between the United States and Russia as a means of resolving differences with respect to Russian-Iran nuclear cooperation.

Chapter 12 — Recommended Analysis, Research, Development, and Demonstration (ARD&D) Program

The government R&D program should support technology required for the global growth scenario. The R&D activity should include diverse activities that balance risk of failure to achieve desired technical advances and the time that such technical advances are needed. Accordingly, *the highest priority in fuel cycle ARD&D, deserving first call on available funds, lies with efforts that enable, for both technical and public acceptance reasons, robust deployment of the open, once-through fuel cycle.*

We give priority to two tasks that are not presently part of the DOE program:

First, we call for a global uranium resource evaluation program to include geological exploration studies to determine with greater confidence the uranium resource base around the world. Our global growth scenario and technology plan are based on the judgment that natural uranium ore is available at reasonable prices to support the open cycle at least until late in the century. We propose $50 million per year for this purpose.

Second, we have been struck throughout our study about the absence of models and simulation that permit quantitative trade-off analysis between different reactor and fuel cycle choices. The analysis we have seen is based on point designs and does not incorporate information about the cost and performance of real nuclear facility operations. Such modeling and analysis, under a wide variety of scenarios, will be useful to the industry and investors, and to international discussions that take place about the desirability of different fuel cycle paths. Every industry in the United States develops basic analytical models and tools, such as spreadsheets, that allow firms, investors, policy makers, and regulators to understand how changes in the parameters of a process will affect the performance and cost of that process. Changes in one feature of a design for the sake of, say, safety may affect other aspects of the design, the overall performance of the system, and the cost of operation. U.S. industries, for example, the chemical processing and commercial aircraft industries, have developed complex analytical models based on extensive engineering and economic information for the purpose of evaluation of alternative courses of action. The DOE nuclear R&D program seems focused on providing information about the operation of a single process, set up in one way. While this program produces knowledge, it does not allow for transferring information to new, related situations and thus provides no foundation for the accumulation of information about how variations in the operation of plants and other parts of the fuel cycle affect costs, safety, waste, and proliferation resistant characteristics.

We call on DOE, perhaps in collaboration with other countries, to establish *a major project for the modeling, analysis, and simulation of commercial nuclear energy systems.* Evidently, the models and analysis should be based on real engineering data, wherever possible, and practical experience. The project should support assessment of reactor concepts and fuel cycles, and acquisition of engineering data on principal technology questions associated with the design of these concepts. This project is technically demanding and will require many years and considerable resources to carry out successfully. To have coherence, the project should have a single program plan and several performers who bring differing ideas and experience to the effort. The project should *not* be given to a single DOE lab or divided into equal shares for all interested DOE labs. We propose $100 million per year for ten years for this purpose.

We believe that development of advanced nuclear technologies — either advanced reactors[1] or advanced fuel cycles[2] — should await the results of the *Nuclear System Modeling Project* we have proposed, (with the exception of advanced design LWRs or R&D on the HTGR, as discussed below). Our analysis makes clear that there is ample time to compile the necessary engineering and economic analysis before undertaking expensive development programs, even if the project should take a decade to complete. A *development and demonstration* program on advanced fuel cycles and advanced reactors is simply not justified on the basis of cost, the unproven safety and waste properties of a closed cycle compared to the open cycle, and proliferation risk. Since deployment of the advanced alternatives is quite far off, efforts should focus on analysis and basic research only, as opposed to development and demonstration, for a considerable period. Costly development projects too far in advance of any credible deployment opportunity can be counterproductive both for optimizing the technology and for supporting the global growth scenario.

On the other hand, we support modest laboratory scale research and analysis on *new* separation methods with the objective to learn about separation methods that are less costly and more proliferation resistant. There has been little exploration in the United States of alternatives to PUREX and pyro-processing since their invention decades ago with entirely different purposes in mind: obtaining weapons usable material and reprocessing metal fuel, respectively. We note however that there is considerable skepticism for even this modest approach, because some see *any* U.S. work on reprocessing sending the wrong signal to other nations about the credibility of our expressed attitude toward the proliferation risks of reprocessing, and the concern that DOE will move from analysis and research to development before the technical basis for such action has been developed. We propose that this program begin at a modest scale, reaching $10 million per year in about five years.

The project's research and analysis effort should stress low cost, safety, and technology pathways that do not produce weapons usable material during operation (for example, by leaving some uranium, fission products and/or minor actinides with the recycled plutonium, which in turn can achieve very high burnup). There are advanced closed fuel cycle concepts[3] of combinations of reactor, fuel form, and separations technology that satisfy these conditions and, with appropriate institutional arrangements, can have proliferation resistance approaching that of the open fuel cycle.

Third, the DOE should, in parallel with the Nuclear System Modeling Project, support R&D on advanced design LWRs and on development of the HTGR that will operate in the open fuel cycle. LWRs will be the main reactor type in a mid-century scenario. The DOE should focus LWR R&D efforts on reducing the capital and operating costs of these reactors, moving to higher burnup fuel, and assuring achievement of improved safety standards. We believe that this program should begin at level of $50 million per year.

The HTGR has certain potential unique safety characteristics and, because of its high efficiency compared to LWRs, the HTGR will use less uranium resource and produce less fission products and actinides than other thermal reactors that produce the same amount of electricity. In addition, the HTGR may have some proliferation resistance advantage, because of the greater difficulty of processing its pellet fuel, although this is, as yet, unproven. The modular nature of the HTGR, with plants designed in the 110 to 300 MWe range, can be a significant advantage for deployment, especially in developing countries using the once-through fuel cycle. However, past operating experience with HTGR plants, at Peachbottom, at Fort St. Vrain, and in Germany is mixed and there is no reliable basis on which to estimate the economics of HTGR plants relative to LWR plants.

We believe the potential advantages of the HTGR justify DOE's support for research and limited development activity, for example measurement and characterization of fuel form behavior and confirmation of performance characteristics of gas power conversion components and suggest a R&D program for this purpose at a level of $30 million per year. The focus should be on moving to the stage where the HTGR can be demonstrated as a potential major contributor for electricity production in the global growth scenario. History suggests a demonstration plant built by the DOE on a DOE facility will not serve to establish the cost of electricity with credibility for investors. Instead, "first mover" assistance to the private sector would be more effective, if further R&D indicates that the HTGR is attractive for electricity production. Establishing the cost of building and operating an HTGR for electricity production is an important milestone for gauging its competitiveness for any application.

The DOE is considering the very high temperature gas reactor (VHTGR) for the purpose of hydrogen production by thermal cracking of water. Moving to very high temperatures will open up the need for still more R&D. With respect to hydrogen production, a major uncertainty lies with the chemical process of thermal cracking of water on an industrial scale and not with the production of high temperature steam, whether from a VHTGR, or any other source.

The *fourth area* that calls for a significant and redirected ARD&D program is waste management. We have emphasized that the DOE waste program has been singularly focused for the past several years on the Yucca Mountain project. As a result much analysis and R&D needed to enable the mid- century scenario has not been undertaken. As discussed in Chapter 11, DOE must broaden its waste R&D effort, or it runs the risk of being unable to rigorously defend its choices for waste disposal sites. Several important programs are required. Characterization of waste forms and engineered barriers, followed by development and testing of engineered barrier systems, is needed. We believe deep boreholes, as an alternative to mined repositories should be aggressively pursued. Reliance on central spent fuel storage facilities will require engineering and development activities on casks, facility design, and transportation.

There is opportunity for international cooperation in this ARD&D program on safety, waste, and the Nuclear System Modeling Project. A particularly pertinent effort is the development, deployment, and operation of a world wide materials protection, control, and accounting tracking system. Cooperation on fuel cycle research will be more sensitive because, as we have stressed, the PUREX/MOX fuel cycle that is currently being pursued in France, Russia, and Japan is *not*, in our view, on the technology pathway to any future desirable closed fuel cycle. Thus, this international collaboration calls for a new international organization for the collaborative research, one that develops and enforces strict guidelines for participation. There currently is no suitable international organization for this task. A possible approach lies with the G-8 as a guiding body. The G-8 has already formed an umbrella structure for dealing with nuclear materials security — the G-8 Global Partnership Against the Spread of Weapons and Materials of Mass Destruction created at the 2002 summit in Canada.

The recommended program is summarized in Table 12.1 with a suggested budget for each category.

Table 12.1 Recommended Federal Analysis, Research, Development, and Demonstration Program (ARD&D) by Priority

R & D TIME PERIOD

RECOMMENDATION #	ECONOMICS	PROLIFERATION	WASTE MANAGEMENT	SAFETY	RESOURCE BASE	NEXT 5 YEARS	5 TO 10 YEARS	LONGER TERM — MAYBE BEYOND 10 YEARS	INCREMENTAL ANNUAL BUDGET $ MILLIONS 0–5 YEARS/5–10 YEARS
1	■				■	Global U ore resource assessment		Unconventional U recovery	50/0
2✻	■	■	■	■	■	Fuel cycle modeling, simulation and analysis project			100/100
3✻			■			Engineered barrier/waste form characterization	Engineered barrier development		50/100
4			■			Deep borehole disposal			50/?
5✻		■	■				Central spent fuel/ high level waste storage		10/50
6	■	■				Lower once-through reactor capital cost	Thermal reactor high burn up fuel	Rarely refueld reactor	50/100
7		■		■			HTGR reactor development ❖		30/30
8				■		Analysis of LWR and fuel cycle safety	Reduce safety risk of LWR and fuel cycle		50/50
9			■				New separations analysis and research ❖	Revisit need for fuel cycle pilot plants †	10/40
10			▄		■			Revisit need for fast reactor development †	—
11✻		■				World wide M,P,C,&A tracking system	Containment, surveillance, and security systems		50/50

✻ Designates special international significance

❖ Could start in earlier period

† Development project starts await outcome of fuel cycle modeling project

NOTES

1. The study of Generation IV reactor concepts would, of course, be part of the assessment project we propose. Government support for reactor development, however, should not be contemplated until after conclusion of the project.
2. The DOE's Advanced Fuel Cycle Initiative calls for the development today of two pilot separation facilities, UREX (a PUREX derivative) and PYROX (an electrometallurgical method), of about 20MTHM/yr capacity in order to make a decision by the year 2007 on a 2000 MTHM/yr plant that would initially operate in 2015. We disagree with the assumptions on which this program is based, in particular that a separation and transmutation approach is needed before Yucca Mountain runs out of its nominal capacity for waste disposal, and that the advanced fuel cycle path will be politically more acceptable, despite its much higher cost, unproved safety and waste properties, and appreciable proliferation risks.
3. There are many reactor concepts. With clear criteria regarding cost, waste, safety, and proliferation resistance, promising concepts are sure to emerge. We mention only two: extremely high burn-up LWRs that can perform a good deal of transmutation in the core, and breed and burn fast reactors that never reprocess.

Glossary of Technical Terms and Abbreviations

TECHNICAL TERMS

Additional protocol
Relative to nonproliferation; an IAEA prerogative for monitoring of undeclared facilities

Blanket
Fast reactor blanket assemblies provide fertile fuel for breeding

Borosilicate glass
Glass “logs” encapsulating high level reprocessing waste

Breeder reactor
A reactor that creates more fissile material than it consumes

Burn up
The thermal energy production of fuel in a reactor

Cap and trade
A program for trading emissions under a national CO_2 cap

Capacity factor
Ratio of actual annual plant electrical production and maximum annual production capability

Carbon emission
Carbon in the form of carbon dioxide in the atmosphere from fossil fuel combustion

Carbon tax
A tax that would be imposed on fuel combustion proportional to carbon dioxide emission

Centrifuge
Centrifuge devices are a method of uranium enrichment

Chain reaction
A nuclear reaction that is sustained in a reactor or critical assembly

Chernobyl
Very severe accident at FSU (Ukranian) nuclear plant in 1986

Closed fuel cycle
A cycle that recovers fissile material from spent fuel, re-fabricates, and reuses it in a reactor

Core damage frequency
Frequency of an accident causing core damage

Conversion
Conversion of natural uranium — yellow-cake — to uranium hexafluride for use in an enrichment plant; and re-conversion to uranium oxide for fuel fabrication

Criticality
Sustained chain reaction

Curie
Unit of radioactive decay; 1 Curie = 3.7 x 10^{10} disintegrations/sec

Decay heat
Heat released by fission products and actinides from reactor operation

Deep borehole
Borehole drilled to several kilometer depth for spent fuel storage

Delayed neutrons
A fraction of fission-born neutrons delayed, easing reactor control

Depleted uranium
Uranium depleted of the U-235 isotope, e.g., enrichment plant tailings

Diffusion
Gaseous diffusion is a process for uranium enrichment

Early site permits
U. S. NRC process for approval of plant sites before actual construction applications

Enriched uranium
Uranium enriched in the U-235 isotope

Enrichment
Separations process that increases the concentration of particular isotopes, such as that of U-235 in natural uranium

Fuel fabrication
Manufacture, processing, and assembly of fuel elements for reactors

Fast reactor
Reactor designed for criticality and operation by fast neutrons

Fast reactor recycle
Reprocessing and recycle of fast reactor fuel, for breeding fuel or other purposes

Fertile fuel
Capable of conversion to a fissile material

First mover
First entity to undertake new plant construction

Fissile fuel
Capable of fission, e.g., U-233, U 235, Pu-239 (and higher odd isotopes)

Fission products
Elements resulting from fission

Geologic repository
Underground storage of spent fuel and/or reprocessing waste

Gigawatt
One billion watts

Heat rate
See BTU/kWhr below

High level waste
Spent fuel or reprocessing waste containing fission products

La Hague
French Reprocessing Plant

Large early release
Major release of radioactivity from reactor containment after a reactor accident

Megawatt
One million watts

Mining and milling
Preparation of natural uranium

Moderator
Substance causing slowing down of fast neutrons by collision; necessary for thermal reactors

Once-through fuel cycle
Fuel used in only one cycle, and there is no reprocessing

Passive systems
Use of stored energy, e.g., gravity, instead of emergency diesels

Price-Anderson act
Government-backed insurance for nuclear power plants

Probabilistic risk assessment
Analysis of reactor accident frequency

Proliferation
Use of processes or technologies to produce nuclear weapons

Pyro-processing
A high temperature electro-chemical separation process for spent fuel

Radioactivity
Emission of alpha or beta particles, or gamma rays from substances by radioactive decay

Radiotoxicity
Radioactive substance health hazard

Reactor
Device utilizing nuclear chain reaction for power production

Reactor core
Assembly of fuel elements in a reactor vessel for sustaining a chain reaction and power production

Reactor vessel head
Top end closure of a reactor vessel

Reactor-years
Measure of reactor experience

Reprocessing
Processing of spent fuel to recover its fissile material

Seed
Central region of a fast reactor core providing power and neutrons

Severe accident
A reactor accident in which fission products and actinides escape from the reactor primary system

Site banking
Obtaining regulatory approval of nuclear plant site before construction

Spent fuel
Fuel removed from reactors at end of its useful life; typically stored in water pools for cooling for ~10 years or more

Spent fuel dry storage
Stored after ~ 10 years in shielded concrete casks

Thermal efficiency
Plant net electrical output divided by thermal input

Thermal reactor
Reactor designed for criticality and operation by thermal (low speed) neutrons

Thermal reactor recycle
Reprocessing and recycle of Plutonium (and Uranium) in thermal reactors

Thorium fuel cycle
A cycle in which fertile Th-232 is converted to fissile U-233

Tonne
Metric ton — 1,000 kilograms

Waste partitioning
Separation of fission products and actinides in spent fuel

Waste transmutation
Reactor transmutation of long-lived fission products or actinides to stable elements or those that are less radiotoxic

ABBREVIATIONS AND UNITS

ARD&D
Analysis, research, development, and demonstration

BTU
British Thermal Unit, i.e., heat required to increase 1 lb. of water by 1 degree Fahrenheit

BTU/kWhr
BTUs of thermal input required to produce 1 kilowatt-hour of electricity

BWR
Boiling Water Reactor: a direct cycle LWR

CANDU
Canadian deuterium-natural uranium reactor

CCGT
Combined cycle gas turbine

CDF
Core damage frequency

Cents/kWe-hr
Cost of electricity per kilowatt-hour

CO_2
Carbon dioxide

COL
U. S. NRC Combined Operation License

$/kg
Natural uranium ore cost

$/kWe
Generating plant capital cost unit

$/MMBTU
Fuel cost unit — dollars per million BTU

$/ton carbon
Carbon tax rate on fuel combustion

DOT
U. S. Department of Transportation

EIA
Energy Information Administration, a part of U. S. DOE

EPA
U. S. Environmental Protection Agency

EPPA
MIT Emissions prediction and policy analysis project

EPRI
Electric Power Research Institute

FP
Fission products

Gen IV
International advanced reactor study underway at DOE

GFC
Gas cooled fast reactor

GHG
Greenhouse gas

GWd
Gigawatt days of thermal energy production

GWe
Gigawatts (1000 megawatt) electric capacity

HDI
United Nations Human Development Index

HEU
Highly enriched (in U-235 isotope) uranium

HLW
High level waste, either in spent fuel, or reprocessing waste

HTGR
High temperature gas cooled reactor

IAEA
International Atomic Energy Agency

INPO
Institute of Nuclear Power Operations, funded by nuclear plant operators for improvement of operations

kWe-hr
Kilowatt-hour of electricity

LER
Large early release of radioactivity from reactor containment after an accident

LMFBR
Liquid metal fast breeder reactor

LWR
Light water reactor, the major power plant type in service

MA
Minor actinides, isotopes heavier that Uranium created in reactors, except for plutonium

MOX
Mixed (Uranium and Plutonium) oxide fuel

MMBTU
Million British thermal units

MPC&A
Fissile materials, production, control, and accountability

MSR
Molten salt reactor

MT
Metric tons

MT/yr
Metric tons per year

MTIHM
Metric tons initial heavy metal (Uranium or Plutonium)

MWe
Mega (million) watts electric capacity

NEA
Nuclear Energy Agency, under the OECD

NOX
Atmospheric oxides of nitrogen

Np-237
Neptunium-237

NPT
Nuclear Nonproliferation Treaty

NSPS
New source performance standards

OECD
Organization for Economic Co-operation and Development

O&M cost
Cost of plant operation and maintenance

PRA
Probabilistic risk assessment

PUREX
Original chemical separation process yielding Plutonium

PWR
Pressurized water reactor, an indirect cycle LWR

Pu-239
Plutonium 239 isotope, a preferred weapons material

R&D
Research and development

RD&D
Research, development, and demonstration

SCWR
Supercritical water reactor

SO_2
Sulfur dioxide

Th
Thorium. Th-232 is fertile, and can be converted to fissile U-233 in a reactor

TMI 2	Three Mile Island Unit 2 nuclear plant
TRU	Transuranic elements, being those having an atomic number higher than uranium
TVA	Tennessee Valley Authority
U-235	Uranium isotope that is least abundant, and fissile/a preferred weapons material capacity
U-238	Uranium isotope that is most abundant
UOX	Uranium oxide
UREX	Separations process for recovery of uranium from spent fuel
U. S. DOE	U. S. Department of Energy
U. S. NRC	U. S. Nuclear Regulatory Commission
YMEs	Yucca Mountain equivalents, referring to fuel storage capacity
WANO	World Association of Nuclear Operators, a world-wide owners group for improvement of operations

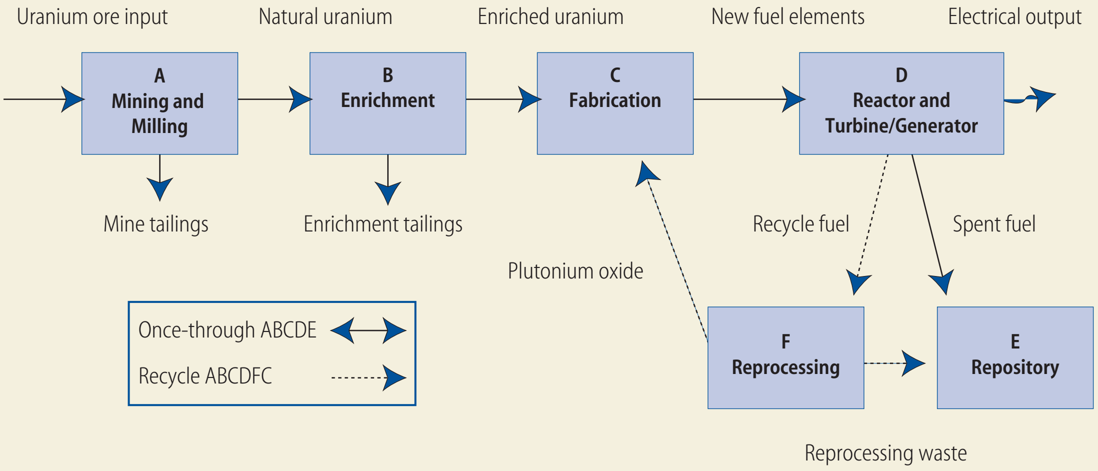
Appendix Chapter 1 — Nuclear Fuel Cycle Primer

INTRODUCTION

This is a Primer to aid understanding of the nuclear fuel cycle. It is intended to explain in layman's terms basic ideas and processes that underlie nuclear power generation, avoiding rigorous discussion of physics and engineering. The bibliography provides references for those who wish to dig deeper into the subjects. Calculations of nuclear fuel cycle quantities are explained in detail in the Chapter 4 Appendix — Fuel Cycle Calculations.

The nuclear fuel cycle consists of the steps required to produce nuclear power, including the input of fissile material, the processes that convert raw material to useful forms, the outputs of energy, and the treatment and/or disposition of spent fuel and various waste streams. The steps appear schematically in Figure A-1.1.

Figure A-1.1 Fuel Cycle Diagram



We will discuss the three main nuclear fuel cycles in the Primer: 1) the Once-through Cycle fueled by enriched uranium, 2) Thermal Reactor Recycle, and 2) Fast Reactor Recycle. We explain these terms as we come to them in the Primer. There are other possible fuel cycles, but these three are the main ones developed to date.

THE NUCLEAR REACTOR

At the heart of the nuclear fuel cycle is the nuclear reactor that generates energy through the fission, or splitting, of uranium and plutonium isotopes (Note: isotopes of an element, such as uranium, have different masses and, as a consequence, virtually identical chemistry but quite different physical behavior). The fission process is caused by neutrons in the reactor core and both liberates considerable energy and produces more neutrons. The energy released is 1 million watt-days per gram of U-235 that undergoes fission, equivalent to 2.5 million times the energy released in burning one gram of coal. The produced neutrons can in turn yield additional fission events, producing a chain reaction that sustains energy production. The probability for a neutron to cause a fission is very high for certain isotopes (in particular, U-235 and Pu-239) when the neutrons are slowed down, or moderated, with respect to the relatively high energy they possess when produced by fission. In a light water reactor (LWR), the moderation is accomplished rapidly by collision of the neutrons with hydrogen nuclei (protons) in the water molecule.

Naturally occurring uranium contains only 0.7% U-235. The rest is U-238, which does not experience fission with slow neutrons. In light water reactors, the fraction of U-235 must be increased through enrichment, typically into the 3-5% range, in order to sustain the chain reaction. In nuclear weapons, by contrast, the enrichment level is generally greater than 90%.

Although the U-238 in the fuel does not contribute directly to energy production with slow neutrons, it does sometimes capture a slow neutron, leading to production of Pu-239, which does contribute to energy production. Indeed a significant part of the energy produced with typical operation of a LWR comes from fission of the Pu-239 produced earlier in the fuel irradiation. The so-called open and closed fuel cycles differ in that the former disposes of the Pu-bearing spent fuel, while the latter captures the U and Pu energy value in irradiated fuel by chemical separation from the fission products and recycle into reactor fuel.

The fission process results in nuclear fragments that generate considerable heat and radioactivity in the spent fuel for a considerable time. These fission-products dominate the nuclear waste problem during the first century, or so. Other nuclear waste components that significantly influence fuel cycle discussions are elements heavier than uranium. Many of these are present in small amounts but, because of long lifetime, play a dominant role after a few hundred years in the residual radiotoxicity. A prime motivation for closed fuel cycles is removal of these very heavy elements.

THE ONCE-THROUGH CYCLE

The Once-through Cycle is the simplest. It appears as ABCDE in Figure A-1.1 of the Fuel Cycle Calculation Primer. It requires uranium ore as input, milling and purification of natural uranium, conversion of the uranium to a chemical form suitable for enrichment, enrichment of the U^{235} isotope[1], fuel fabrication, loading of uranium fuel assemblies in a reactor, and then reactor operation. At the end of useful life, spent fuel is removed from the reactor, stored in a pool of water for cooling and shielding of radioactivity, then removed and placed in air-cooled casks at reactor sites for interim storage, and finally removed to geologic waste storage, as in the plan for Yucca Mountain in Nevada. Long-term isolation and heat removal from spent fuel is necessary to prevent release of radioactive isotopes to ground water near a repository. Spent fuel fission product radioactive decay and heat generation continues for hundreds of years, and in smaller quantities for many thousands of years.

URANIUM MINING

Natural uranium ore is broadly distributed in the world. Large deposits usually contain 1% or less, but there are some rich deposits in Canada and Australia containing up to 10% to 20% natural uranium. About 200 metric tons of natural uranium are required annually for a 1000 Mwe LWR, or about 100,000 metric tons of ore containing 0.2 % natural uranium. Rich deposits also leave behind less mining residue, i.e., tailings. For this reason rich deposits are usually more economical to mine than low grade deposits. Uranium mine tailings are by far the largest quantity of fuel cycle waste.

URANIUM PROCESSING AND FUEL MANUFACTURING

Processing of natural uranium into fuel rods and assemblies for Light Water Reactors (LWRs) is a complex step because of the need for enrichment of the U^{235} isotope. There are two methods of enrichment in commercial use in the nuclear industry, both depending on the fact that U^{235} is slightly lighter in atomic weight than the more plentiful U^{238} isotope. Gaseous diffusion is one method: uranium hexafluoride gas diffuses through porous barriers, in which the lighter isotope U^{235} in a molecule of gas passes the barrier more quickly than the heavier, thereby permitting isotopic separation. Many stages of separation are required to obtain the required enrichment, and the process consumes much electricity for pumping the hexafluoride gas through the plant systems.

Separation by centrifuge is the second method. In principle the process is simple: uranium hexafluoride gas flows through a rapidly spinning centrifuge; centrifugal force presses the heavier gas molecule, $U^{238}F_6$, toward the centrifuge outside wall, yielding two streams, one enriched, and the other depleted in the lighter molecule. The system transfers the enriched stream to higher stages until the required enrichment is achieved. Centrifuge separation uses much less electricity per unit of separative work than the gaseous diffusion process.

Emerging technologies, such as laser isotope separation, may eventually lower cost. However, even before reaching commercial viability, such technologies could contribute to proliferation if applied to relatively small amounts of uranium.

Conversion of enriched uranium hexafluoride gas to uranium dioxide is the next step. Zirconium is the material of choice for fuel cladding, because zirconium is a very weak absorber of neutrons, an important characteristic in reactors as we shall see. In Pressurized Water Reactors[2] (PWR), the loaded fuel rods are formed into fuel assemblies in a 17x17 square array of fuel rods, held firmly in place so that they will not shift position in the fuel assembly either in transportation or in the reactor. BWR fuel assemblies have a smaller cross-section and contain fewer fuel rods than PWR fuel assemblies.

NUCLEAR REACTOR OPERATION

Control of a nuclear chain reaction is just as important as creating it in the first place. Control rods that contain neutron absorbers such as boron are one method of control. Inserting a control rod into the reactor core captures neutrons so that they cannot then cause fission, and power generation decreases. Withdrawal of a control rod has the opposite effect. Coordinating control rod movement with measurement of power level makes possible adjustment to a desired level. Another method of control utilizes the moderator for this purpose: increasing the temperature of cooling water in LWRs causes the moderator to expand, become less dense, and therefore less effective as a moderator. A decrease in moderator density causes power to decrease. LWRs depend on this effect for an important property that aids self-regulation of power.

Most of the neutrons born of fission are prompt, that is to say they appear almost immediately at the instant of fission. A fraction of them, about 0.65% in the case of U^{235} fission, is delayed. Delayed neutrons are late arrivals, coming in delay groups with half-lives ranging from a quarter of a second to almost a minute. Delayed neutrons make possible reactor control with simple control systems. In effect delayed neutrons buy time for reactor control systems to function. Control systems, however, must assure that increases in neutron production do not exceed the delayed neutron fraction. Otherwise the reactor would become prompt critical, and fission rate would increase exponentially and very rapidly.

We briefly describe power conversion in LWRs. The PWR is an indirect cycle that transports heat from the reactor core to steam generators that raise steam in a separate, indirect cycle. Steam in the indirect cycle drives a steam turbine and electrical generator. The BWR design is direct cycle, and steam produced in the reactor flows directly to the BWR steam turbine. Both cycles have their advantages and disadvantages, but the two have remained competitive through several generations of plant designs.

HIGH TEMPERATURE GAS COOLED REACTORS (HTGR)

A brief description of the HTGR[3] follows. It differs from a conventional LWR in a number of respects, one being high temperature of operation, i.e., about 900º Centigrade at the reactor core outlet, a fact that allows a conversion efficiency of about 45% compared to 33% in the case of LWRs. Helium is the reactor core coolant, and also drives the turbine for the power conversion cycle and the compressors.

Currently there are two concepts under development for commercial use: the Prismatic Fuel Modular Reactor (GT-MHR) by General Atomics Co., and the Modular Pebble Bed Reactor (MPBR) by Eskom, the South African state electric company.

The GT-MHR has evolved from Fort St. Vrain technology, using coated micro-spheres of fuel in more or less conventional fuel assemblies, and having the capability to retain fission products at high temperatures in case of a reactor accident. It employs a direct cycle, i.e., helium from the outlet of the reactor core drives the power conversion turbine and the compressors that force helium back through the reactor. The proposed plant has a thermal rating of 600 MWth, and 286 MWe net output. The reactor vessel is of a size comparable to LWR reactor vessels. This fact, together with lower power output, has the result of smaller core power density than is the case with LWRs (see discussion in the section on Reactor Safety in Chapter 6). Due to smaller unit output, multiple units are required to produce an output equivalent to one conventional LWR plant.

The MPBR is based on German technology developed for an experimental plant and a demonstration plant during the 1960s to 1980s. The Eskom project began in 1993, and is now in the early stages of licensing in South Africa. The plant rating is 400 MWth, and 165 MWe net output. It differs from the GT-MHR concept in its use of fuel in the form of "pebbles", i.e., a ball, coated with pyrolytic carbon, about 2 inches in diameter that contains micro-spheres of fuel that are similar to those used in the GT-MHR fuel. In operation the MPBR reactor vessel contains about 450,000 of these fuel balls. The advantage of this configuration is that it allows refueling while at power: fuel balls are continuously added to and removed from the reactor, and the plant does not require shutdown for the purpose of refueling. The MPBR also differs from the GT-MHR in its use of an indirect cycle: helium reactor coolant flows to an intermediate heat exchanger and transfers heat to the secondary power conversion cycle that drives the turbine. Because the reactor cooling and power conversion cycles are separate, there is no radioactive carryover from the reactor to the power conversion system. Due to the temperature drop across the intermediate heat exchanger, there is some loss of efficiency, but handling of the fuel balls would be considerably more difficult if a direct cycle were employed.

Both the GT-MHR and the MPBR have smaller electrical output than conventional LWRs. How can their cost compete with the LWR? The answer is that LWRs and HTGRs follow different economic scaling laws. LWR experience has shown that the incremental cost of larger plant output, i.e., $/kWe of investment, declines with larger plants. The economics of the smaller HTGRs, however, depend on factory manufacture of modules for assembly at the plant site, on shorter construction schedules, and on completing units sequentially, one year apart. The idea is that these three factors taken will make investments productive sooner and make multiple HTGR units competitive with the single unit LWR, but this is, as yet, unproven.

SPENT FUEL

When reactor operation has used as much of the new fuel enrichment as possible, fuel assemblies becomes spent fuel. Spent nuclear fuel is radioactive and heat producing. Typical LWR spent fuel today reaches a burnup of 50,000 MWD/MT[4]. One year after removal from the reactor the total radioactivity is about 3 million curies/metric ton including alpha particle, beta particle, and gamma ray decay, and the decay heat rate is about 13 kWth/metric ton (kilowatts thermal per metric ton). After 10 years these quantities decrease to about 0.6 million curies/metric ton, and 2 kwth/metric ton.

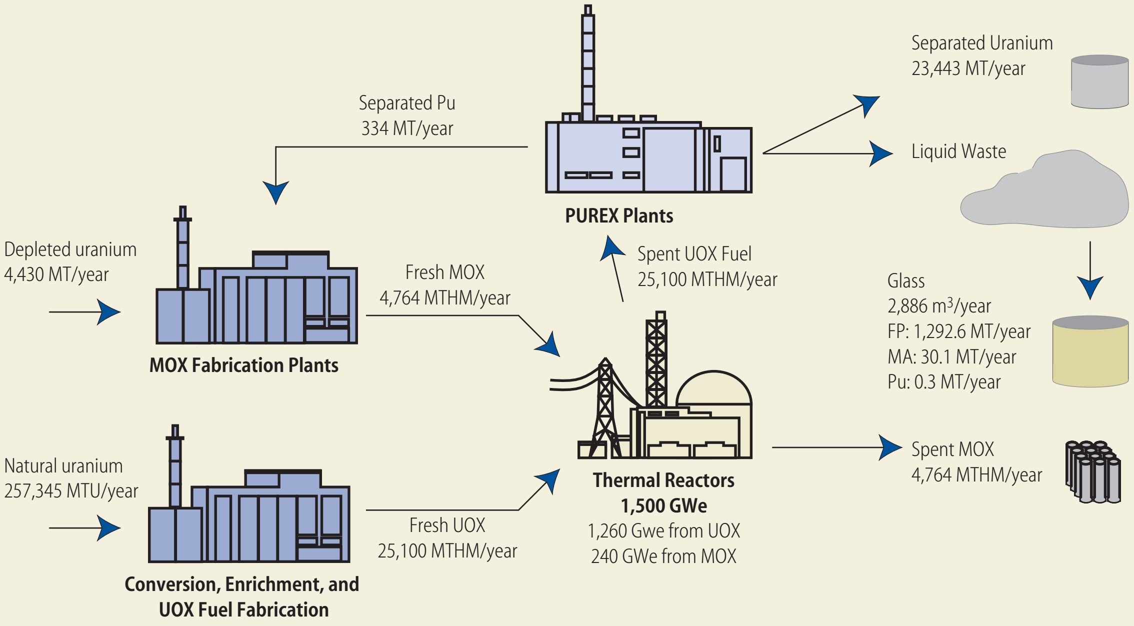
In the U. S. today, spent fuel is stored at individual reactor sites in large pools of water for at least 10 years. After that it is stored in large concrete casks that provide air cooling, shielding and physical protection. These casks can hold 20-24 Pressurized Water Reactor (PWR) fuel assemblies, or twice that number of Boiling Water Reactor (BWR) fuel assemblies. The assemblies are sealed in a helium atmosphere inside the cask to prevent corrosion. Decay heat is transferred by helium from the fuel to fins on the outside of the storage cask for air-cooling. Eventually all spent fuel will be moved from reactor sites to underground geologic storage, such as at Yucca Mountain in Nevada. Transportation of these assemblies will require large rail and trucking equipment, and careful traffic planning. Shipping cask development is well advanced for many fuels. Shipping casks typically are able to carry 7 PWR fuel assemblies, or 18 BWR assemblies. The casks were designed to withstand high-speed truck and railroad train collisions without loss of integrity[5], including subjection to fires along the way.

Having described removal of spent fuel to storage in a geologic repository, we have completed description of the once-through fuel cycle.

THERMAL REACTOR RECYCLE

Plutonium production in the once-through fuel cycle represents a significant energy resource, but requires reprocessing of spent fuel to recover the plutonium and to fabricate new fuel. Recycling of fuel can be done in thermal reactors, or in fast reactors. We consider first thermal reactor recycle, which appears as ABCDFC in Figure A-1.1.

Figure A-1.2 Closed Fuel Cycle: Plutonium Recycle (MOX option - one recycle) — Projected to 2050



Thermal recycle adds another process in comparison with the once-through cycle, i.e., fuel reprocessing mentioned in the preceding paragraph. France, Japan, Russia, and the United Kingdom have reprocessing plants in operation. In 1976–77 Presidents Ford and Carter stopped commercial reprocessing in the U. S. The technology employed in commercial reprocessing to the present has its roots in the Manhattan Project during World War II. It includes the following steps: a) waiting for spent fuel radioactive decay to reduce radiation and heat generation; b) remote cladding removal ("de-cladding") so as to separate it from the fuel; c) dissolving the fuel pellets in nitric acid; and finally d) separation of uranium and plutonium by solvent extraction. When separation is complete, the uranium and plutonium products are returned to the fuel preparation and fabrication steps of the once-through cycle. For recycle fuel fabrication, however, shielded fabrication lines are needed for worker protection. One of the options for waste management in the separations process is to collect the fission products and actinides, and seal them in glass "logs" for waste disposal in long-term geologic storage. The quantity of radioactive material contained in the glass logs is approximately the same as the amounts remaining in spent fuel assemblies of the once-through cycle (i.e., the fission product inventory is the same).

If the enriched uranium and plutonium are recovered from spent fuel and re-fabricated into mixed oxide (MOX) fuel rods and assemblies, the result at best will be a reduction of new fuel required by about 30% compared to the once-through fuel cycle, recycled uranium and plutonium making up the difference. Spent fuel reprocessing is very costly, and, given the market price of natural uranium ore for the foreseeable future and the cost of enrichment, thermal recycle is not an economic choice.

SAFETY AND SAFEGUARDS

Consideration of safety and safeguards is necessary in design and operation of a reprocessing plant, because of the large inventory of radioactive fuel cycle waste and fissile material. The radioactive materials must be controlled and contained. In contrast to a reactor, a reprocessing plant must not go "critical" and have a fission chain reaction. This requires strict control over all materials in the plant at all times. Quantities and mixtures of fissile materials must be limited so that there is insufficient material present at any time to become critical, and start a nuclear chain reaction. Fire and explosion must be precluded, and leaks of tanks that store or carry fissile materials or radioactive waste must be prevented, or at the least detected and contained. Worker safety and control of plant personnel radiation exposure is a major requirement. Reprocessing plants may produce considerable quantities of radioactive and toxic chemical wastes that arise in the reprocessing process.

FAST REACTOR RECYCLE

A fast breeder reactor is capable by design of producing more fissile isotopes than it consumes, thus making it possible to provide a growing energy resource that does not require a continuing supply of U^{235} or Pu^{239} after an initial investment of fissile fuel at the beginning of its life. Breeder reactor cores typically have two regions: a "seed" region on the inside of the core, and a "blanket" region surrounding the "seed". "Seed" fuel assemblies consist of fissile fuel, 15%-20% fissile plutonium, and this region provides power and fission neutrons to maintain criticality, while "blanket" assemblies contain fertile fuel, U^{238}, for breeding of new plutonium. A diagram for the fast reactor fuel cycle appears in Figure A-1.1. Although the details of fast reactor fuel reprocessing differ from thermal reactor recycle, the two have similar reprocessing diagrams and process steps.

There are important differences between fast and thermal reactors, including the high energy fast neutrons, and the need to eliminate neutron moderators, i.e., water, and other materials that cause neutrons to lose energy and become thermal neutrons. As a result certain liquid metals such as sodium, or lead-bismuth, are used for cooling the fast reactor fuel instead of water. Because the probability of neutron absorption in fissile fuel is low in a fast reactor, the reactor core must have a high concentration of fissile isotopes. Comparison of fast reactor and LWR cores shows that there is more fissile material per unit of volume than in LWRs. Fuel enrichment for fast reactors is higher, i.e., 15%-20%, than it is in LWRs. The core is compact, and there must be both high coolant flow rate and large heat transfer area to remove heat from the core. This is accomplished by means of closely packed fuel rods of smaller diameter than in LWRs. We note that neutron balance requires very close attention in fast reactors fueled by Pu^{239}, because the fraction of delayed neutrons is only ⅓ of the U^{235} delay fraction. As a result, a fast reactor can become prompt critical with just ⅓ of the reactivity increase needed to make a U^{235} thermal reactor prompt critical.

Fast reactor technology is very demanding, and more capital intensive than LWR technology. A fast reactor power generation economy would also bring reprocessing and large amounts of fissile material with weapons potential into commercial use. Such a development would raise major safeguards and security concern, which is discussed in Chapter 8.

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NOTES

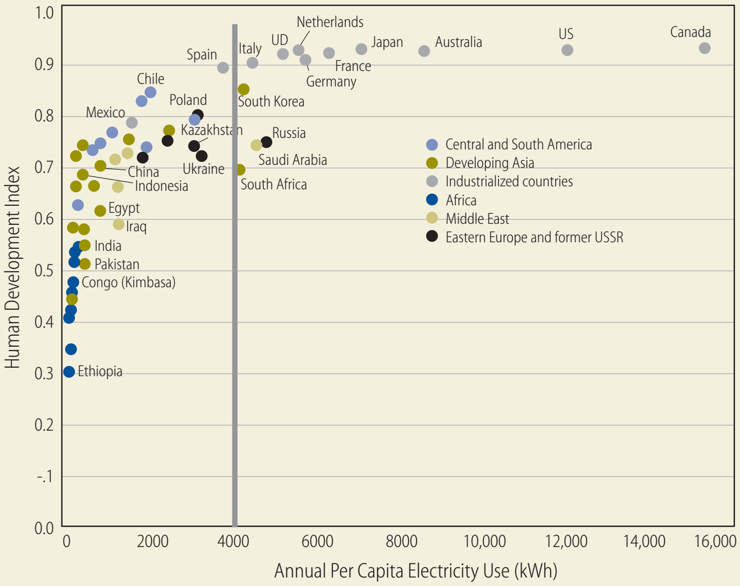
1. Natural uranium consists of 0.71% U^{235} by weight, and the remainder is U^{238}.
2. The PWR is one of the two types of LWR, the other being the Boiling Water Reactor (BWR).
3. The UK has extensive experience with CO_2 cooled gas reactors. In the U. S. Fort St. Vrain operated for 11 years before shut down in 1989. The Fort St. Vrain reactor coolant also was CO_2, with an intermediate heat exchanger, and a steam driven turbine.
4. The heat energy produced by fission is called burnup, and is expressed in megawatt-days per metric ton (MWD/MT). The designation "per metric ton" generally refers to "heavy metal" meaning the tons of total fissile and fertile material as metal; mostly uranium in the case of LWRs
5. Terrorist attack on spent fuel shipment was not considered originally, and this possibility requires safety review.

Appendix Chapter 2 — Global Electricity Demand and the Nuclear Power Growth Scenario

The United States National Academy of Engineering declared electrification as the leading engineering accomplishment of the twentieth century. This recognition, for a century of extraordinary technological developments, acknowledges the profound impact of electricity on quality of life and suggests that governments around the world will continue to attach very high priority to providing adequate electricity infrastructure and supply to their citizens, within their means to make such investments. Today the per capita consumption of electricity spans three orders of magnitude, as shown in Figure A-2.1 (S. Benka, Physics Today (April 2002) p.38). The empirical dividing line between advanced and developing economies, as represented by the United Nations Human Development Index (HDI), is 4000 kWh per person per year electricity use. The HDI is based on health, education, and economic criteria.

The underlying assumption in our mid-century electricity demand scenario is that the developed countries continue with a modest annual increase in per capita electricity use and the developing countries move to the 4000 kWh per person per year benchmark if at all feasible. Specifically, we have taken developed country annual per capita electricity growth rates between 0.5% and 1%, values that bracket EIA expectations for the United States over the next twenty years (EIA Annual Energy Outlook, 2001); over the last quarter century, the growth rate averaged about 2%, falling to 1.5% in 2000 and expected to decline further in the years ahead. We present the 1% case in our table below. We take the same per capita growth rate for the Former Soviet Union countries. Although these are not necessarily robust economies today, they do enjoy substantial per capita electricity use already. Total electricity production is then computed using the United Nations population projections to mid-century.

Figure A-2.1 Correlation between HDI and Per Capita Electricity Consumption



For the developing economies, we assume that the investments needed to reach the 4000 kWh per capita benchmark will be a high priority. When this is combined with the UN population projections, the total electricity production growth rate is then calculated. For example, China needs a 2.9% annual growth rate in per capita electricity use and a 3.2%

annual growth rate in total electricity production to mid-century in order to reach the per capita benchmark.

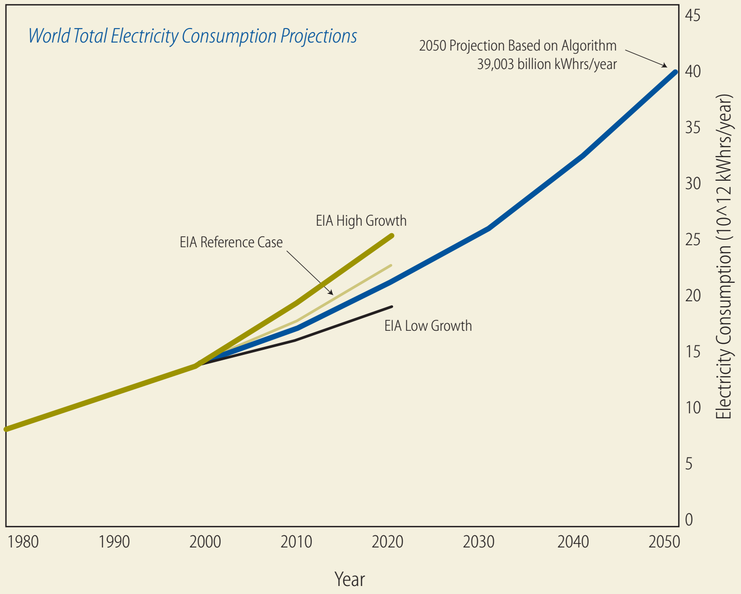
For the countries further down the curve in Figure A-2.1, this algorithm would produce unreasonable growth rates. In other words, the per capita benchmark is not realistically achievable in the mid-century time frame. We have limited total electricity growth rate to 4.7% per year, which is 0.5% higher than the EIA's projected average (to 2020) for all developing countries combined (recall that we have lower growth rates for the more advanced developing countries).

This algorithm suggests a classification into various categories:

- Developed countries (e.g., US, Japan, Germany,…)
- Former Soviet Union (e.g., Russia,…)
- More advanced developing countries: those that can achieve 4000 kWh per person per year within the cap on annual electricity production growth rate (e.g., China, Brazil, Mexico, Iran, Egypt,…)
- Less advanced developing countries: those that cannot achieve the per capita benchmark within the cap, but can reach "acceptable" levels in the 1500 to 4000 kWh per capita range (e.g., India, Indonesia, Pakistan, Philippines, Vietnam,…)
- Least developed countries: those that reach less than 1000 kWh per person per year even at the cap (e.g., Nigeria, Bangladesh, Democratic Republic of the Congo, Ethiopia,…).

The result for individual countries, excluding the large number of nations with populations below three million, is shown in Table A-2.1 (reference: C. M. Jones, MIT M.S. thesis, 2003; a listing for all countries can be found there).

Figure A-2.2 Comparison of TEC Projections (1% per year per capita increase)



It is easy to see the inverse correlation between level of development and population increase within the developing country categories as constructed above. The global electricity use generated by this algorithm lies between the EIA's "business-as-usual" and "low growth" scenarios, as shown in Figure A-2.2.

Finally, we use this pattern of electricity demand to estimate the nuclear power market share for each country in the context of a robust global growth scenario. This is certainly not a prediction of rapid growth in nuclear power. Rather, it is an attempt to understand what the distribution of nuclear power deployment would be if robust growth were realized, perhaps driven by a broad commitment to reducing greenhouse gas emissions and a concurrent resolution of the various challenges confronting nuclear power's acceptance in various countries.

Within this context, our judgment on nuclear power market share is based on various country-specific factors, such as current nuclear power deployment, urbanization, stage of economic development, and energy resource base. Table A-2.1 explicitly shows the range of market share taken for each country, leading to the nuclear power demand map that shaped some of our recommendations, particularly those dealing with nonproliferation concerns.

Several comments are in order. First, we do not anticipate any nuclear power deployment in the least developed countries. Second, the developed nations remain the locus for a major part of nuclear power deployment in the growth scenario. In particular, the United States, because of the very large demand increase associated with its economic strength and projected large population increase, must experience very substantial expansion of its nuclear reactor fleet if the global growth scenario is to be realized. In addition, nations such as Germany, where there is currently strong anti-nuclear sentiment, would almost certainly need to participate. This is indicative of the substantial difficulty inherent in having nuclear power expand several-fold by mid-century.

Among the developing nations, India and China clearly are the major contributors to growth of nuclear power in the growth scenario. However, as nuclear weapons states, these are not the drivers of our nonproliferation considerations. Rather, it is the remaining countries in the "more advanced" and "less advanced" developing categories that shape our nonproliferation discussion. These countries account for about 10% of deployed mid-century nuclear power in the global growth scenario.

Table A-2.1a Electricity Consumption Projections (Developed World)

COUNTRY	TOTAL POPULATION (millions)		TOTAL ELECTRICITY CONSUMPTION (billion kWhrs)		PER CAPITA CONSUMPTION (kWhrs/per)		NUCLEAR PRODUCTION (billion kWhrs)						NUCLEAR EQ. "CAPACITY" (GWe)			%/year TEC	%/year LOW NUCLEAR	%/year HIGH NUCLEAR
DEVELOPIED WORLD	**2000**	**2050**	**2000**	**2050***	**2000**	**2050***	**2000**	**%**	**2050 L**	**% L**	**2050 H**	**% H**	**2000**	**2050 L**	**2050 H**			
USA	283	397	3,621.0	8,349	12,785	21,026	717	20%	2,505	30%	4,174	50%	82	286	477	1.7%	2.5%	3.6%
France	59	62	408.5	701	6,896	11,342	315	77%	561	80%	596	85%	36	64	68	1.1%	1.2%	1.3%
Japan	127	109	943.7	1,334	7,425	12,212	274	29%	534	40%	800	60%	31	61	91	0.7%	1.3%	2.2%
Germany	82	71	501.7	712	6,117	10,061	151	30%	285	40%	427	60%	17	33	49	0.7%	1.3%	2.1%
Korea, South (ROK)	47	52	254.1	461	5,436	6,980	97	38%	230	50%	323	70%	11	26	37	1.2%	1.8%	2.4%
United Kingdom	59	59	345.0	563	5,807	9,551	79	23%	169	30%	281	50%	9	19	32	1.0%	1.5%	2.6%
Canada	31	40	499.8	1,080	16,249	26,724	60	12%	324	30%	540	50%	7	37	62	1.6%	3.4%	4.5%
Spain	40	31	201.2	259	5,040	8,289	56	28%	104	40%	156	60%	6	12	18	0.5%	1.2%	2.1%
Sweden	9	8	139.2	201	15,740	25,887	51	37%	101	50%	141	70%	6	11	16	0.7%	1.3%	2.0%
Belgium	10	10	78.1	120	7,623	12,537	45	58%	72	60%	96	80%	5	8	11	0.9%	0.9%	1.5%
Taiwan	22	23	139.0	233	6,277	8,054	35	25%	93	40%	140	60%	4	11	16	1.0%	2.0%	2.8%
Finland	5	5	82.0	122	15,848	26,064	23	28%	49	40%	73	60%	3	6	8	0.8%	1.5%	2.4%
Switzerland	7	6	52.6	68	7,338	12,069	19	37%	34	50%	47	70%	2	4	5	0.5%	1.1%	1.8%
Netherlands	16	16	100.7	165	6,349	10,441	4	4%	17	10%	33	20%	0	2	4	1.0%	2.9%	4.3%
Norway	4	5	112.5	202	25,172	41,399	0	0%	20	10%	40	20%	0	2	5	1.2%	—	—
Australia	19	27	188.5	429	9,849	16,198	0	0%	43	10%	86	20%	0	5	10	1.7%	—	—
New Zealand	4	4	33.3	64	8,818	14,503	0	0%	6	10%	13	20%	0	1	1	1.3%	—	—
Austria	8	6	54.8	72	6,778	11,147	0	0%	7	10%	14	20%	0	1	2	0.5%	—	—
Denmark	5	5	33.9	53	6,377	10,488	0	0%	0	0%	0	0%	0	0	0	0.9%	—	—
Israel	6	10	34.9	96	5,777	9,501	0	0%	10	10%	19	20%	0	1	2	2.0%	—	—
Ireland	4	5	20.8	48	5,475	9,005	0	0%	0	0%	0	0%	0	0	0	1.7%	—	—
China, Hong Kong	7	8	35.4	63	4,975	8,182	0	0%	0	0%	0	0%	0	0	0	1.2%	—	—
Italy	58	43	283.7	348	4,932	8,111	0	0%	35	10%	70	20%	0	4	8	0.4%	—	—
Greece	11	9	46.1	64	4,345	7,146	0	0%	0	0%	0	0%	0	0	0	0.7%	—	—
Subtotal	**924**	**1,010**	**8,211**	**15,810**	**8,888**	**15,659**	**1,926**	**23%**	**5,197**	**33%**	**8,071**	**51%**	**220**	**593**	**921**	**1.3%**	**2.0%**	**2.9%**

Table A-2.1b Electricity Consumption Projections (More Advanced Developing)

COUNTRY ***DEVELOPIING WORLD*** ***More Advanced***	**TOTAL POPULATION (millions)**		**TOTAL ELECTRICITY CONSUMPTION (billion kWhrs)**		**PER CAPITA CONSUMPTION (kWhrs/per)**		**NUCLEAR PRODUCTION (billion kWhrs)**						**NUCLEAR EQ. "CAPACITY" (GWe)**			**%/year TEC**	**%/year LOW NUCLEAR**	**%/year HIGH NUCLEAR**
	2000	**2050**	**2000**	**2050***	**2000**	**2050***	**2000**	**%**	**2050 L**	**% L**	**2050 H**	**% H**	**2000**	**2050 L**	**2050 H**			
Kuwait	2	4	29.0	100	15,157	24,927	0	0%	0	0%	0	0%	0	0	0	2.5%	—	—
United Arab Emirates	3	4	36.0	84	13.811	22,714	0	0%	0	0%	0	0%	0	0	0	1.7%	—	—
Singapore	4	5	25.9	49	6,458	10,620	0	0%	0	0%	0	0%	0	0	0	1.3%	—	—
Saudi Arabia	20	60	114.9	554	5,645	9,284	0	0%	0	0%	0	0%	0	0	0	3.2%	—	—
Puerto Rico	4	5	19.1	39	4,869	8,008	0	0%	0	0%	0	0%	0	0	0	1.4%	—	—
Bulgaria	8	5	34.4	32	4,330	7,121	15	44%	16	50%	23	70%	2	2	3	–0.1%	0.1%	0.8%
South Africa	43	47	181.5	326	4,191	6,893	13	7%	65	20%	130	40%	1	7	15	1.2%	3.3%	4.8%
Portugal	10	9	41.1	61	4,108	6,756	0	0%	6	10%	12	20%	0	1	1	0.8%	—	—
Hungary	10	7	35.1	43	3,521	5,791	14	40%	22	50%	26	60%	2	2	3	0.4%	0.9%	1.2%
Libya	5	10	18.0	56	3,411	5,609	0	0%	6	10%	11	20%	0	1	1	2.3%	—	—
Brazil	170	247	360.6	989	2,116	4,000	4	1%	148	15%	297	30%	0	17	34	2.0%	7.7%	9.2%
Mexico	99	147	182.8	587	1,849	4,000	7	4%	88	15%	176	30%	1	10	20	2.4%	5.1%	6.6%
Iraq	23	54	25.4	214	1,106	4,000	0	0%	0	0%	0	0%	0	0	0	4.4%	—	—
Costa Rica	4	7	5.9	29	1,465	4,000	0	0%	0	0%	0	0%	0	0	0	3.2%	—	—
Ecuador	13	21	9.7	85	764	4,000	0	0%	0	0%	0	0%	0	0	0	4.4%	—	—
Cuba	11	11	13.8	43	1,235	4,000	0	0%	0	0%	0	0%	0	0	0	2.3%	—	—
Algeria	30	51	21.8	205	721	4,000	0	0%	20	10%	41	20%	0	2	5	4.6%	—	—
Thailand	63	82	90.3	330	1,437	4,000	0	0%	33	10%	66	20%	0	4	8	2.6%	—	—
Syria	16	36	17.7	145	1,092	4,000	0	0%	0	0%	0	0%	0	0	0	4.3%	—	—
Egypt	68	114	64.7	455	953	4,000	0	0%	46	10%	91	20%	0	5	10	4.0%	—	—
Malaysia	22	38	58.6	151	2,637	4,000	0	0%	15	10%	30	20%	0	2	3	1.9%	—	—
Chile	15	22	37.9	89	2,491	4,000	0	0%	0	0%	0	0%	0	0	0	1.7%	—	—
Mongolia	3	4	2.7	17	1,078	4,000	0	0%	0	0%	0	0%	0	0	0	3.7%	—	—
Turkey	67	99	114.2	395	1,713	4,000	0	0%	40	10%	79	20%	0	5	9	2.5%	—	—
Oman	3	9	7.5	35	2,968	4,000	0	0%	0	0%	0	0%	0	0	0	3.1%	—	—
Croatia	5	4	12.6	17	2,716	4,000	0	0%	0	0%	0	0%	0	0	0	0.6%	—	—
Peru	26	42	18.3	168	713	4,000	0	0%	0	0%	0	0%	0	0	0	4.5%	—	—
China	1,275	1,462	1,206.3	5,848	946	4,000	12	1%	877	15%	1,754	30%	1	100	200	3.2%	9.0%	10.5%
Argentina	37	55	80.8	218	2,182	4,000	6	7%	44	20%	87	40%	1	5	10	2.0%	4.2%	5.6%
Lebanon	3	5	8.6	20	2,472	4,000	0	0%	0	0%	0	0%	0	0	0	1.7%	—	—
Uruguay	3	4	7.4	17	2,203	4,000	0	0%	0	0%	0	0%	0	0	0	1.7%	—	—
Albania	3	4	5.4	16	1,716	4,000	0	0%	0	0%	0	0%	0	0	0	2.2%	—	—
Jordan	5	12	7.1	47	1,443	4,000	0	0%	0	0%	0	0%	0	0	0	3.8%	—	—
Korea, North (DROK)	22	28	31.1	112	1,395	4,000	0	0%	22	20%	45	40%	0	3	5	2.6%	—	—
Venezuela	24	42	75.1	169	3,107	4,000	0	0%	17	10%	34	20%	0	2	4	1.6%	—	—
Dominican Republic	8	12	8.8	48	1,052	4,000	0	0%	0	0%	0	0%	0	0	0	3.4%	—	—
Poland	39	33	119.3	133	3,091	4,000	0	0%	13	10%	27	20%	0	2	3	0.2%	—	—
Jamaica	3	4	6.3	15	2,433	4,000	0	0%	0	0%	0	0%	0	0	0	1.8%	—	—
Zimbabwe	13	24	10.5	94	830	4,000	0	0%	0	0%	0	0%	0	0	0	4.5%	—	—
Colombia	42	71	40.3	283	958	4,000	0	0%	0	0%	0	0%	0	0	0	4.0%	—	—
Tunisia	9	14	9.6	56	1,011	4,000	0	0%	0	0%	0	0%	0	0	0	3.6%	—	—
Bosnia and Herzegovina	4	3	2.6	14	648	4,000	0	0%	0	0%	0	0%	0	0	0	3.4%	—	—
Iran	70	121	111.9	486	1,591	4,000	0	0%	97	20%	194	40%	0	11	22	3.0%	—	—
Romania	22	18	45.7	73	2,036	4,000	5	10%	15	20%	22	30%	1	2	2	0.9%	2.3%	3.2%
Yugoslavia	11	9	31.5	36	2,989	4,000	0	0%	0	0%	0	0%	0	0	0	0.3%	—	—
Panama	3	4	4.7	17	1,629	4,000	0	0%	0	0%	0	0%	0	0	0	2.6%	—	—
El Salvador	6	11	4.1	41	648	3,749	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—

Table A-2.1c Electricity Consumption Projections (Less Advanced Developing)

COUNTRY *DEVELOPING WORLD*	TOTAL POPULATION (millions)		TOTAL ELECTRICITY CONSUMPTION (billion kWhrs)		PER CAPITA CONSUMPTION (kWhrs/per)		NUCLEAR PRODUCTION (billion kWhrs)						NUCLEAR EQ. "CAPACITY" (GWe)					
Less Advanced	**2000**	**2050**	**2000**	**2050***	**2000**	**2050***	**2000**	**%**	**2050 L**	**% L**	**2050 H**	**% H**	**2000**	**2050 L**	**2050 H**	**%/year TEC**	**%/year LOW NUCLEAR**	**%/year HIGH NUCLEAR**
India	1,009	1,572	509.9	5,099	505	3,243	15	3%	765	15%	1,530	30%	2	87	175	4.7%	8.1%	9.6%
Philippines	76	128	37.8	378	500	2,946	0	0%	38	10%	76	20%	0	4	9	4.7%	—	—
Morocco	30	50	14.3	143	480	2,849	0	0%	14	10%	29	20%	0	2	3	4.7%	—	—
Honduras	6	13	3.6	36	560	2,797	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Indonesia	212	311	86.1	861	406	2,765	0	0%	172	20%	344	40%	0	20	39	4.7%	—	—
Sri Lanka	19	23	6.2	62	325	2,669	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Bolivia	8	17	3.6	36	433	2,125	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Zambia	10	29	5.8	58	560	1,995	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Vietnam	78	124	24.0	240	307	1,937	0	0%	24	10%	48	20%	0	3	5	4.7%	—	—
Nicaragua	5	11	2.2	22	429	1,896	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Guatemala	11	27	4.8	48	421	1,807	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Pakistan	141	344	58.3	583	413	1,694	1	1%	87	15%	175	30%	0	10	20	4.7%	10.5%	12.1%
Paraguay	5	13	2.0	20	355	1,552	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—

Table A-2.1d Electricity Consumption Projections (Least Developed)

COUNTRY *DEVELOPING WORLD*	TOTAL POPULATION (millions)		TOTAL ELECTRICITY CONSUMPTION (billion kWhrs)		PER CAPITA CONSUMPTION (kWhrs/per)		NUCLEAR PRODUCTION (billion kWhrs)						NUCLEAR EQ. "CAPACITY" (GWe)					
Least Advanced	**2000**	**2050**	**2000**	**2050***	**2000**	**2050***	**2000**	**%**	**2050 L**	**% L**	**2050 H**	**% H**	**2000**	**2050 L**	**2050 H**	**%/year TEC**	**%/year LOW NUCLEAR**	**%/year HIGH NUCLEAR**
Papua New Guinea	5	11	1.5	15	319	1,397	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Ghana	19	40	5.5	55	284	1,369	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Ivory Coast	16	32	3.6	36	222	1,103	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Cameroon	15	32	3.4	34	227	1,044	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Kenya	31	55	4.4	44	145	801	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Myanmar	48	69	4.5	45	94	656	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Senegal	9	23	1.2	12	130	541	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Nigeria	114	279	14.8	148	130	530	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Bangladesh	137	265	12.5	125	91	473	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Tanzania	35	83	2.6	26	75	316	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Yemen	18	102	3.0	30	162	291	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Sudan	31	64	1.8	18	59	288	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Nepal	23	52	1.4	14	62	273	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Congo, DR	51	204	4.6	46	90	225	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Angola	13	53	1.1	11	84	208	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Uganda	23	102	1.3	13	56	129	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Ethiopia	63	186	1.5	15	24	81	0	0%	0	0%	0	0%	0	0	0	4.7%	—	—
Subtotal *	**4,614**	**7,395**	**4,224**	**21,315**	**916**	**2,882**	**91**	**2%**	**2,690**	**13%**	**5,347**	**25%**	**10**	**307**	**610**	**3.3%**	**7.0%**	**8.5%**

** For all developing countries in Tables A2.1 b, c, and d.*

Table A-2.1e Electricity Consumption Projections (Former Soviet Union)

COUNTRY	TOTAL POPULATION (millions)		TOTAL ELECTRICITY CONSUMPTION (billion kWhrs)		PER CAPITA CONSUMPTION (kWhrs/per)		NUCLEAR PRODUCTION (billion kWhrs)						NUCLEAR EQ. "CAPACITY" (GWe)			%/year TEC	%/year LOW NUCLEAR	%/year HIGH NUCLEAR
Former Soviet Union	2000	2050	2000	2050*	2000	2050*	2000	%	2050 L	% L	2050 H	% H	2000	2050 L	2050 H			
Russia	145	104	767.1	904	5,272	8,671	115	15%	271	30%	452	50%	13	31	52	0.3%	1.7%	2.8%
Ukraine	50	30	151.7	120	3,061	4,000	65	43%	60	50%	72	60%	7	7	8	–0.5%	–0.2%	0.2%
Slovakia	5	5	25.2	36	4,668	7,678	12	48%	22	60%	25	70%	1	2	3	0.7%	1.2%	1.5%
Czech Republic	10	8	54.7	74	5,325	8,758	10	19%	22	30%	30	40%	1	3	3	0.6%	1.5%	2.1%
Lithuania	4	3	6.9	12	1,866	4,000	5	77%	10	80%	10	85%	1	1	1	1.1%	1.2%	1.3%
Slovenia	2	2	10.6	13	5,342	8,786	4	35%	7	50%	8	60%	0	1	1	0.5%	1.2%	1.6%
Armenia	4	3	4.9	13	1,291	4,000	2	32%	5	40%	6	50%	0	1	1	1.9%	2.4%	2.8%
Estonia	1	1	5.4	5	3,848	6,329	0	0%	0	0%	0	0%	0	0	0	–0.2%	—	—
Tajikistan	6	10	12.5	39	2,060	4,000	0	0%	0	0%	0	0%	0	0	0	2.3%	—	—
Kazakhstan	16	15	48.3	61	2,989	4,000	0	0%	6	10%	12	20%	0	1	1	0.5%	—	—
Uzbekistan	25	41	41.9	162	1,684	4,000	0	0%	16	10%	32	20%	0	2	4	2.7%	—	—
Moldova	4	4	3.7	14	851	4,000	0	0%	0	0%	0	0%	0	0	0	2.8%	—	—
Kyrgyzstan	5	8	9.8	30	1,995	4,000	0	0%	3	10%	6	20%	0	0	1	2.3%	—	—
Belarus	10	8	26.8	33	2,629	4,000	0	0%	3	10%	7	20%	0	0	1	0.4%	—	—
Georgia	5	3	7.9	13	1,499	4,000	0	0%	1	10%	3	20%	0	0	0	1.0%	—	—
Turkmenistan	5	8	7.7	34	1,627	4,000	0	0%	3	10%	7	20%	0	0	1	3.0%	—	—
Azerbaijan	8	9	16.7	36	2,075	4,000	0	0%	4	10%	7	20%	0	0	1	1.5%	—	—
Subtotal	**306**	**261**	**1,202**	**1,598**	**3,925**	**6,118**	**213**	**18%**	**433**	**27%**	**677**	**42%**	**24**	**49**	**77**	**0.6%**	**1.4%**	**2.3%**
TOTALS	**5,844**	**8,666**	**13,636**	**38,723**	**2,333**	**4,468**	**2,230**	**16%**	**8,321**	**21%**	**14,094**	**36%**	**255**	**950**	**1,609**	**2.1%**	**2.7%**	**3.8%**

*** Table represents 1% per year increase in electricity consumption from 2000 to 2050**

**** 2050 after cutoff numbers**

***** Countries ranked by 2000 nuclear production**

Appendix Chapter 4 — Fuel Cycle Calculations

THERMAL ONCE-THROUGH URANIUM FUEL CYCLE

The majority of the world's nuclear electricity production is based on the once-through fuel cycle using enriched uranium in light water reactors (LWR). This fuel cycle is represented in Figure A-4.1 below. Note that the specific numerical mass flows and enrichments in Figure A-4.1 are for a burnup of 33 GWd/MTIHM, which was the average burnup for U.S. reactors about 2 decades ago. In the rest of this section, we use a burnup of 50 GWd/MTIHM, which is currently the average for U.S. PWRs.

Figure A-4.1 can be greatly simplified by lumping together all the front-end operations, all the back-end operations, and neglecting losses (typically about 0.5% in any given stage. In addition, the enrichment tails are of little interest because, although they are produced in significant amounts, they are low level wastes and can be managed easily. Figure A-4.2 shows a simplified representation of the once-through fuel cycle for 1500 GWe of LWR reactors operating under today's conditions of 50 GWd/MTIHM burnup and 90% capacity factor. The enrichment tails, which are low level wastes produced in significant amounts, are not explicitly considered here. The mass flows that appear in Figure A-4.2 are obtained from the analysis presented next. Note that Figure A-4.2 and the calculations that follow apply to PWRs (for simplicity, we assume PWR characteristics for all LWRs. BWRs differ principally in that the fuel requires lower initial enrichment and achieves lower burnup, which would slightly decrease the required natural uranium feed and slightly increase the mass of spent fuel produced).

Figure A-4.2 Once-through Fuel Cycle (simplified)

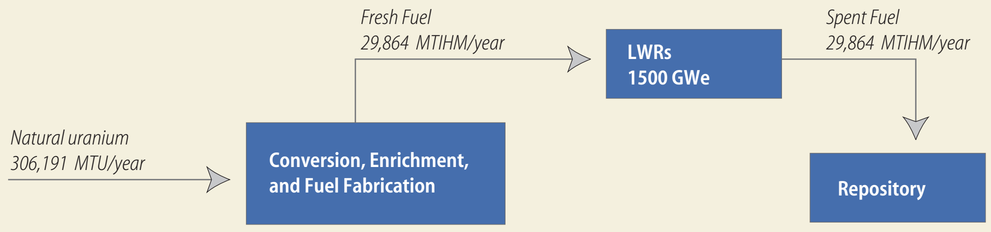
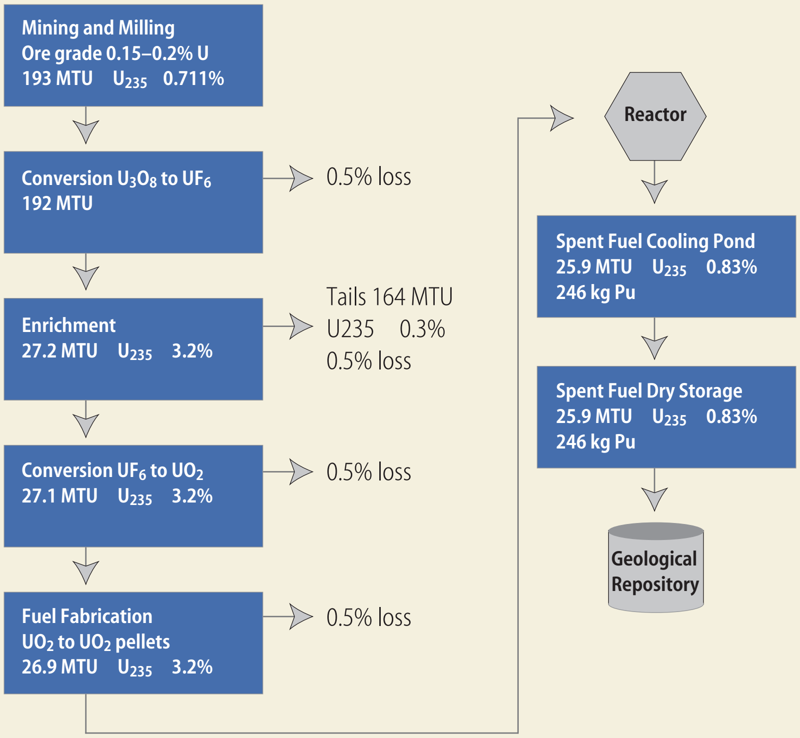


Figure A-4.1 Once-through Fuel Cycle



Source: Adapted from Appendix C, Norman Rasmussen MIT & Allen Croff ORNL, Nuclear Wastes, National Research Council, p.135 (1996).

The amount of energy produced per unit mass of fuel[1] is called the fuel burnup, measured in GWd/MTIHM[2]. The burnup will vary with reactor design and fuel management schemes. In the U.S, pressurized water reactors (PWR) reach a burnup of approximately 50 GWd/MTIHM. This value is used for the calculations presented in this section. The mass of fuel that must be loaded into the reactors per year[3] is obtained as:

$$M = \frac{Q}{B_d} \qquad [1]$$

where:
M: mass of fuel loaded per year (MTIHM/year)
Q: annual thermal energy output (GWd/year)
Bd: discharge burnup (GWd/MTIHM)

The annual thermal energy output is given by the following expression:

$$Q = \frac{P_e \cdot CF \cdot 365}{\eta_{th}} \qquad [2]$$

where:
Pe: installed electric capacity (GWe)
CF: capacity factor
η_{th}: thermal efficiency (effectively GWe/GWth)

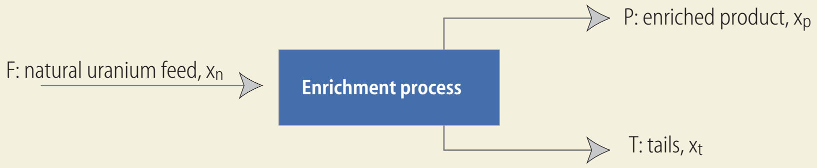
Combining equations [1] and [2], we obtain:

$$M = \frac{P_e \cdot CF \cdot 365}{\eta_{th} \cdot B_d} \qquad [3]$$

The capacity factor of nuclear power plants in the U.S. is about 90% and the thermal efficiency of LWR power plants is approximately 33%. Hence, using equation [3] with an installed capacity of 1500 GWe, we find that the mass of fuel loaded in the reactors every year is 29,864 MTIHM.

The mass of natural uranium required for fuel production can be obtained by considering the enrichment process (the variable x designates enrichment):

Figure A-4.3 Enrichment Process



The enrichment of natural uranium is x_n=0.711% and the enrichment of tails is assumed to be x_t=0.30%. From mass conservation of U-235 in the enrichment process:

$$\frac{F}{P} = \frac{X_p - X_t}{X_n - X_t} \qquad [4]$$

Hence, for a given product mass of enriched uranium, *P*, the mass of natural uranium feed required, *F*, depends on the enrichment x_p. For PWRs, the required enrichment for a given burnup can be approximated using the following correlation[4] (valid for enrichments up to 20%):

$$x_p = 0.41201 + 0.11508 \cdot \left(\frac{n+1}{2n} \cdot B_d\right) + 0.00023937 \cdot \left(\frac{n+1}{2n} \cdot B_d\right)^2 \qquad [5]$$

where n is the number of fuel batches, i.e. the fraction of the core refueled per cycle is 1/n.

The number of batches is selected according to the fuel management scheme adopted by the reactor operator. In the U.S., the number is typically approximately 3. Using equation [5] with n=3 and B_d=50 GWd/MTIHM, the resulting U-235 enrichment is x_p=4.51%. Using (4), we find F/P=10.25, and hence the mass of natural uranium required is 306 191 MT/yr for the needed 29,864 MTIHM/yr of enriched uranium to load the 1500 GWe reactor fleet.

The contents of spent fuel discharged from the reactors can be roughly divided into 4 categories: 1) uranium; 2) plutonium; 3) fission products (FP); 4) minor actinides (MA). The content of spent fuel irradiated to 50 GWd/MTIHM is as follows: 93.4% uranium (with a U-235 enrichment of 1.1%), 5.15% fission products, 1.33% plutonium, and 0.12% minor actinides.[5]

Since the mass of spent fuel unloaded per year is 29,864 MTIHM[6], the total amounts of these materials discharged in a year for a 1500 GWe installed capacity are: 27 893 MT of uranium, 1538 MT of fission products, 397 MT of plutonium, and 36 MT of minor actinides as tabulated in Table A-4.1.

Table A-4.1 Spent Fuel Material Flows — Once-through (1500 GWe at 90% capacity)

	50 GWd/MTIHM	100 GWd/MTIHM
Spent Fuel (MTIHM/yr)	29,864	14,932
Spent Fuel Composition		
U	93.4% (27 893 MT/yr)	87.43% (13 055 MT/yr)
FP	5.15% (1538 MT/yr)	10.30% (1538 MT/yr)
Pu	1.33% (397 MT/yr)	1.97% (294 MT/yr)
MA	0.12% (36 MT/yr)	0.30% (45 MT/yr)

High Burnup Case

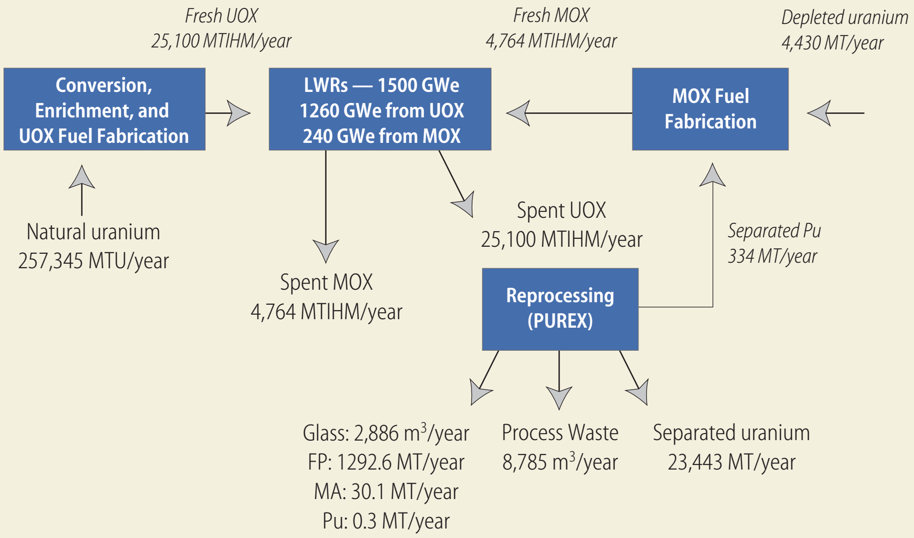
If the burnup is increased to 100 GWd/MTIHM, the mass of fuel loaded and discharged per year is reduced by a factor of 2 to 14,932 MTIHM/yr. The enrichment required, using (5), is 9.15%, giving a natural uranium consumption of 321,447 MT/yr for the current typical 3-batch fuel management scheme. This value is 5% higher than with current burnup. If a 5-batch fuel management scheme is adopted in this case, the required enrichment is 8.18%, giving a natural uranium consumption of 286,231 MT/yr (8% lower than with current burnup).

It is important to note that the gross amount of fission products generated to produce a given amount of electricity is independent of fuel burnup because the energy yield of fission is always 1000 $\mathrm{GWd/MTHM_{fissioned}}$. Therefore, in the case of high burnup fuel, the same amount of material must be fissioned and the same quantity of fission products is generated, but the fission products are simply concentrated in a smaller mass of fuel. The content of spent fuel at 100 GWd/MTIHM is as follows: 87.43% uranium (with a U-235 enrichment of 1.66%), 10.30% fission products, 1.97% plutonium, and 0.30% minor actinides.[7] The total amount of material discharged per year is therefore: 13 055 MT of uranium, 1538 MT of fission products, 294 MT of plutonium, 45 MT of minor actinides as tabulated in Table A-4.1. We note that the amount of plutonium discharged per year is lower than for a burnup of 50 GWd/MTIHM.

THERMAL FUEL CYCLE WITH SINGLE-PASS PLUTONIUM RECYCLING

The plutonium present in spent fuel can be recycled and used as fissile material in new nuclear fuel. Recycled plutonium is mixed with natural or depleted uranium to make MOX fuel (Mixed OXide fuel), typically composed of 7% PuO_2 and 93% UO_2. A fuel cycle where all the UOX spent fuel (but none of the MOX spent fuel) is recycled for MOX fabrication is represented in Figure A-4.4.[8] The mass flows that appear in Figure A-4.4 are obtained from the analysis presented next.

Figure A-4.4 Plutonium Single-recycle — 1,500 GWe Fleet



The LWR fleet considered is fueled with both UOX and MOX. By design, an individual reactor can be fueled by UOX only or by a mix of UOX and MOX. In practice, current reactors employing UOX and MOX are fueled with a 2:1 ratio of UOX to MOX fuel.

For simplicity, we assume that MOX fuel is irradiated to the same burnup as UOX fuel, 50 GWd/MTIHM.[9] We shall also assume that all power plants have a thermal efficiency of 33% and a capacity factor of 90%. If all the spent UOX fuel was reprocessed and all the plutonium it contains was recycled to make MOX fuel, the fraction of nuclear capacity that could be based on MOX can be determined as follows:

Using equation [3] to determine the mass of spent UOX discharged per year:

$$\text{Mass of spent UOX} = \frac{(P_e)_{UOX} \cdot 0.9 \cdot 365}{0.33 \cdot 5.0} \quad \text{[MTIHM per year]}$$

Recalling that spent UOX fuel has plutonium content of 1.33% and assuming that 99.9% of this plutonium can be recovered by PUREX (equivalently 0.1% of the plutonium is lost during reprocessing):

$$\text{Pu recycled from spent UOX} = \frac{(P_e)_{UOX} \cdot 0.9 \cdot 365}{0.33 \cdot 5.0} \cdot 0.0133 \cdot 0.999 \ \ [\text{MT Pu per year}]$$

The mass of MOX fuel needed per year is also determined using equation [3]:

$$\text{Mass of MOX} = \frac{(P_e)_{MOX} \cdot 0.9 \cdot 365}{0.33 \cdot 5.0} \cdot [\text{MTIHM per year}]$$

And since MOX fuel has an initial plutonium content of 7%:[10]

$$\text{Pu needed for MOX} = \frac{(P_e)_{MOX} \cdot 0.9 \cdot 365}{0.33 \cdot 5.0} \cdot 0.07 \ \ [\text{MT Pu per year}]$$

If we now require that the amount of plutonium recycled from spent UOX be equal to the amount of plutonium needed for MOX fabrication, we find:

$$\frac{(P_e)_{UOX}}{(P_e)_{MOX}} = \frac{0.07}{0.0133 \cdot 0.999} = 5.27$$

Note that the value that is most frequently used for this ratio is 7 in current conditions. This is because the plutonium content of spent fuel is usually taken as 1% (this is a good approximation for UOX fuel irradiated to a burnup of 30 to 40 GWd/MTIHM).

Once the UOX to MOX ratio is known, the mass flows in Figure A-4.4 are obtained using equations [3] through [5] as follows: for a total capacity of 1500 GWe and a UOX:MOX ratio of 5.27, we have 1260 GWe based on UOX and 240 GWe based on MOX. Using equation [3] we find a throughput of 25 100 MTIHM/yr for UOX and 4 764 MTIHM/yr for MOX. Using equation [4], the mass of natural uranium required for UOX fabrication is 257 345 MT/yr.

The spent UOX is sent to reprocessing. For the PUREX Process, we assume that all the fission products, all of the minor actinides, and 0.1% of the plutonium present in the spent UOX fuel are separated and incorporated in borosilicate glass. The volume of borosilicate glass is 0.115 m^3 per MTIHM of fuel reprocessed. In addition, PUREX generates radioactive process waste at a rate of 0.35 m^3 per MTIHM of fuel reprocessed.[11] Assuming once again that the spent UOX contains 93.4% uranium, 5.15% fission products, 1.33% plutonium, and 0.12% minor actinides, we find that the borosilicate glass contains 1292.6 MT/yr of fission products, 30.1 MT/yr of minor actinides, and 0.3 MT/yr of plutonium. The amount of separated uranium is 23 443 MT/yr, and 334 MT/yr of separated plutonium is available for MOX fabrication. Since the total mass of MOX is 4 764 MTIHM/yr, the depleted uranium requirement is 4 430 MT/yr.

The total plutonium content of MOX fuel decreases by approximately 30% during irradiation in the reactor;[12] since fresh fuel has plutonium content of 7%, the spent fuel has a content of approximately 4.9%. As seen in Figure A-4.4, 4 764 MTIHM of MOX is discharged from the reactors each year, so the total amount of plutonium discharged is approximately 233 MT/yr. This is a reduction of 40% compared to a once-through cycle (recall that the mass of plutonium discharged in the once-through case was 397 MT/yr). Indeed, although the spent MOX fuel has a higher plutonium content than spent UOX (4.9% vs. 1.23%), the mass of spent MOX discharged is much smaller and the total amount of plutonium in spent fuel is lower. In addition, the plutonium discharged in spent MOX has a degraded isotopic composition (i.e. more Pu-238 and Pu-240) and is therefore less suitable for weapon production. However, because the PUREX process produces separated plutonium, the MOX cycle is generally viewed unfavorably in terms of proliferation resistance.

We note that the natural uranium consumption in this case is only about 15% lower than in the once-through case. Hence the MOX option has only a modest impact in improving utilization of uranium resources. This could be improved if the uranium separated by the PUREX process was recycled and re-enriched to make new fuel. At present, separated uranium is not recycled because its isotopic composition would complicate enrichment plant operations (e.g. significant U-236 is present) and because uranium ore is inexpensive. If uranium ore prices increased or enrichment costs decreased, re-enrichment of separated uranium for production of UOX fuel could become an attractive option. Currently, however, separated uranium is stockpiled for possible future use. Multiple-pass recycling is another option that, although not attractive under current conditions, could further reduce uranium consumption.

Finally, we note that approximately 25,100 MTIHM of spent fuel need to be reprocessed every year in this 1500 GWe scenario. The La Hague COGEMA reprocessing plant has a capacity of 1,700 MTHM /y. Therefore this scenario requires about 15 La Hague equivalent reprocessing plants. Table A-4.2 tabulates these spent fuel material flows for this single pass plutonium recycle case.

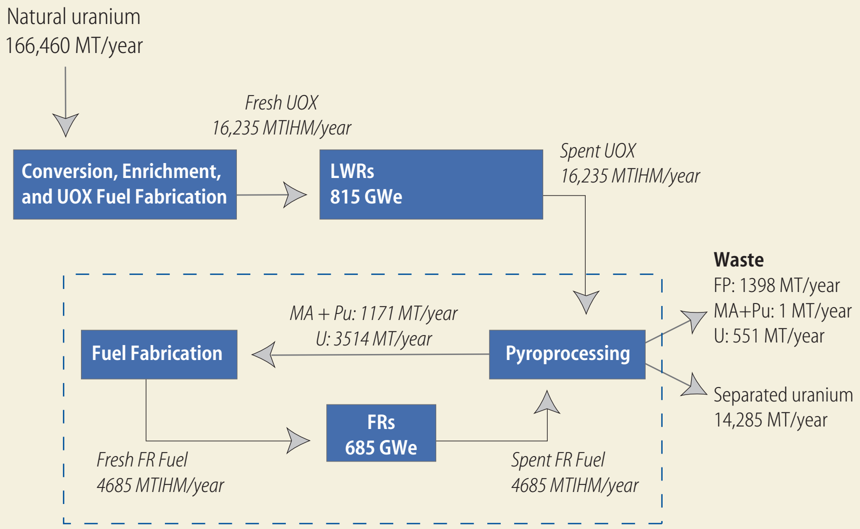
Table A-4.2 Spent Fuel Material Flows—Single-Pass Pu Recycling (1500 GWe at 90% capacity)

Reprocessed UOX	25,100 MTIHM/yr
Separated U	23,443 MT/yr
Borosilicate Glass	
FP	1292.6 MT/yr
MA	30.1 MT/yr
Pu	0.3 MT/yr
Spent MOX (MTIHM/yr)	4 764 MT/yr
Pu (4.9%)	233 MT/yr

BALANCED FUEL CYCLE WITH FAST AND THERMAL REACTORS

The main purpose of recycling spent fuel in the MOX fuel cycle is to recover fissile plutonium and use it to produce energy. However, if fast reactors[13] (FR) are used, all the plutonium and minor actinides can be recycled, incorporated into new fuel, and fissioned in a fast neutron flux. In this way, uranium resources are utilized much more efficiently, and the radiotoxicity of spent nuclear fuel is greatly reduced. A fuel cycle where FRs are used in tandem with LWRs is shown in Figure A-4.5 (note that we assume that all the spent fuel, including the LWR spent fuel, is pyroprocessed):

Figure A-4.5 FR/LWR Balanced Fuel Cycle — 1,500 GWe Fleet



The mass of fuel loaded each year in the LWRs and the FRs is determined using equation (3). For the FR, a burnup of 120 GWd/MTIHM, a thermal efficiency of 40%, and a capacity factor of 90% are assumed. The composition of heavy metal in FR fuel is taken as 75% uranium and 25% transuranics (plutonium and minor actinides). If we assume that the FRs are operated as burners such that the transuranics content of the fuel decreases by 20% during irradiation,[14] the ratio of FR capacity to LWR capacity can be determined as follows:

The annualized mass of FR fuel is given by equation [3]:

$$\text{Mass of FR fuel} = \frac{(\text{Pe})_{FR} \cdot 0.9 \cdot 365}{0.4 \cdot 120} \quad [\text{MTIHM per year}]$$

The mass of plutonium and minor actinides that must be supplied for the fabrication of FR fuel is (recalling that FR fuel contains 25% transuranics):

$$\text{Pu} + \text{MA needed for FR} = \frac{(\text{Pe})_{FR} \cdot 0.9 \cdot 365}{0.4 \cdot 120} \cdot 0.25 \; [\text{MT Pu} + \text{MA per year}]$$

Since the transuranics content of the fuel has been assumed to decrease by 20% during irradiation, we have:

$$\text{Pu + MA from spent FR fuel} = \frac{(Pe)_{FR} \bullet 0.9 \bullet 365}{0.4 \bullet 120} \bullet 0.25 \bullet (1 - 0.2) \text{ [MT Pu + MA per year]}$$

The mass of spent UOX is obtained using equation [3]:

$$\text{Mass of spent UOX} = \frac{(P_e)_{UOX} \bullet 0.9 \bullet 365}{0.33 \bullet 50}$$

Since spent UOX contains 1.33% plutonium and 0.12% minor actinides, the annualized mass of plutonium and minor actinides is:

$$\text{Pu + MA from spent UOX} = \frac{(Pe)_{UOX} \bullet 0.9 \bullet 365}{0.33 \bullet 50} \bullet 0.0145 \text{ [MT Pu + MA per year]}$$

Assuming that 99.9% of the Pu and MA can be recovered in pyroprocessing, we get:

$$\text{Pu + MA for FR fuel} = 0.999 \bullet \begin{bmatrix} \text{Pu + MA from} \\ \text{spent FR fuel} \end{bmatrix} + \begin{bmatrix} \text{Pu + MA from} \\ \text{spent UOX} \end{bmatrix}$$

From the expression above, we find the ratio of installed electric power capacity of FRs to LWRs:

$$\frac{(P_e)_{FR}}{(P_e)_{UOX}} = \frac{0.0145 \bullet 0.4 \bullet 120}{0.25 \bullet 0.33 \bullet 50 \bullet \left({}^{1}/_{0.999} - (1 - 0.2) \right)} = 0.84$$

Therefore, if total nuclear capacity is 1500 GWe, the FR capacity can be taken as 685 GWe and the LWR capacity can be taken as 815 GWe. Using equation (3), we find that the mass of fuel required for the LWRs and FRs is 16,235 MTIHM/yr and 4,685 MTIHM/yr respectively. Using equation (4), we find that the amount of natural uranium required for UOX fuel fabrication is 166,460 MT/yr, about 60% less than for the once-through case.

Note that the FR:LWR capacity ratio is dependent on the assumptions made regarding FR fuel composition: if the fraction of transuranics in FR fuel coming from reprocessed UOX was lower than 20%, there would be a lower LWR share of total capacity. Furthermore, if the total transuranics content of FR fuel were reduced below 25%, the LWR capacity would decrease.

With full actinide recycle, the bulk of the wastes from pyroprocessing is composed of fission products (the waste also contains 0.1% of the actinides, which come from losses during reprocessing). The quantity of fission products generated in a given year by the FRs can be obtained by assuming that, in a fast reactor, fission produces 1000 $GWd/MTHM_{fissioned}$ on average. Hence, using equation (2) to get the annual thermal output, Q (GWd), and dividing by 1000 $GWd/MTHM_{fissioned}$, we obtain the annualized production of fission products:

$$FP_{FR} = \frac{685 \cdot 0.9 \cdot 365}{0.4 \cdot 1000} = 562 \ \text{[MT FP per year]}$$

The reprocessed LWR fuel (16,235 MT/yr) contains 5.15% fission products, or 836 MT/yr, leading to a total discharge in fission products of 1398 MT/yr for this fuel cycle.

The production of the FR fuel (4,685 MTIHM/yr), assuming it is composed of 25% transuranics and 75% uranium, requires 1171 MT of transuranics and 3,514 MT of uranium. Assuming 0.1% losses in transuranics during reprocessing, the input of transuranics to pyroprocessing must be 1172 MT (1 MT of this amount will end up in the waste).

The amount of separated uranium can be obtained as follows: the total mass of spent FR fuel is 4,685 MTIHM/yr. The spent fuel contains 563 MT of fission products and 80% of the initial 1171 MT of transuranics, or 937 MT. The remaining mass, or 3,185 MT, is uranium. The spent UOX fuel (16,235 MTIHM/yr) contains 93.4% uranium (see Table A-4.1), or 15 164 MT. Therefore, the total uranium input to pyroprocessing is 18,349 MT. Due to process limitations in pyroprocessing, 3% of this amount, or 551 MT, is discharged with the waste. Since only 3,513 MT are required for FR fuel fabrication, the amount of separated uranium to be stockpiled is 14,285 MT/yr. Table A-4.3 tabulates these spent fuel material flows for this balanced FR/LWR fuel cycle.

Table A-4.3 Spent Fuel Material Flows — Balanced FR/LWR (1500 GWe at 90% capacity)

Reprocessed UOX	16,235 MTIHM/yr
Reprocessed FR fuel	4,685 MTIHM/yr
Separated U	14,285 MT/yr
Pyroprocessing waste:	
FP	1398 MT/yr
Actinides (Pu+MA)	1 MT/yr
Uranium	551 MT/yr

Current Situation: Once-Through with Some Plutonium Recycle

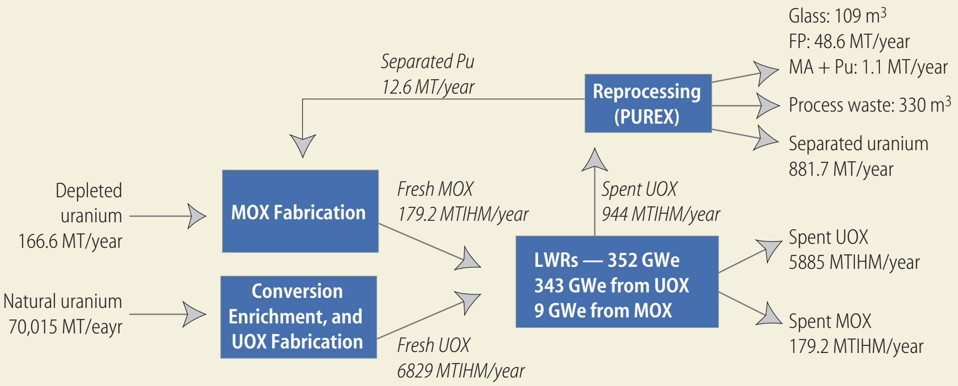
The simple models developed so far to evaluate mass flows in various fuel cycles can be applied to the current world nuclear fleet. Of course, this will only yield a rough estimate of the actual quantities involved because the models are greatly simplified.

As of 2002, the installed world nuclear capacity based on thermal reactors is approximately 352 GWe. For simplicity, we will assume that all reactors are LWRs, and we apply the same assumptions as before for burnup (50 GWd/MTIHM), capacity factor (90%), and thermal efficiency (33%). MOX fuel currently represents approximately 2.5% of world nuclear fuel production,[15] so we assume that 9 GWe of installed capacity is based on MOX.

Table A-4.4 Spent Fuel Material Flows — Existing World Fleet Modeled as LWRs on a Once-through Fuel Cycle with Some Pu Recycle (352 GWe at 90% capacity)

Spent UOX	5 885 MTIHM/yr
Pu (1.33%)	78 MT/yr
Spent MOX	179.2 MTIHM/yr
Pu (4.9%)	9 MT/yr
Reprocessed UOX	944 MTIHM/yr
Separated U	881.7 MT/yr
Borosilicate Glass:	
FP	48.6 MT/yr
Pu+MA	1.1 MT/yr

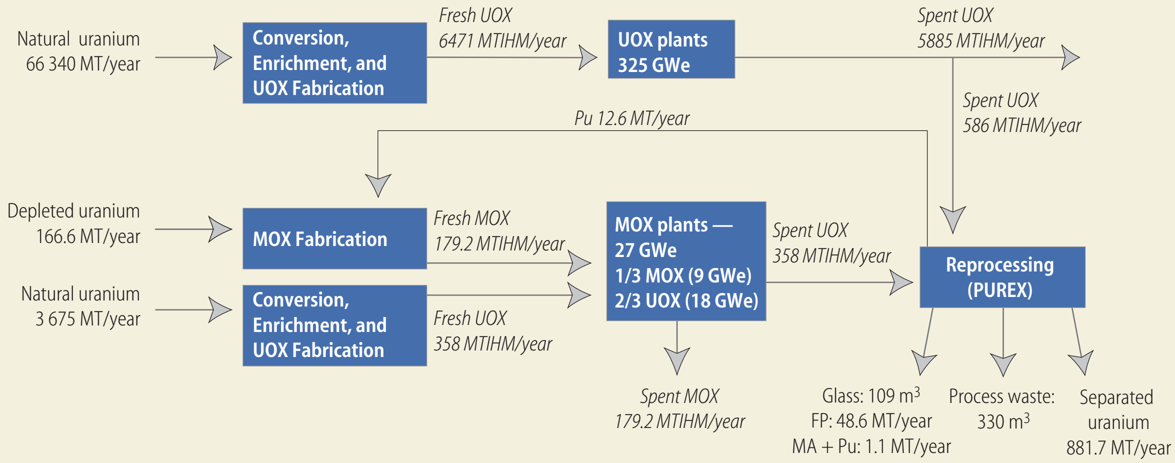
Figure A-4.6 Once-through Cycle with Some Plutonium Recycling — 352 GWe Fleet



The mass flows in Figure A-4.6 are calculated using equations (3) to (5), recalling that spent UOX fuel is composed of 93.4% uranium, 5.15% FP, 1.33% Pu, and 0.12% MA and that fresh MOX has a plutonium content of 7%. The spent fuel material flows for this fuel cycle are summarized in Table A-4.4.

It is interesting to consider how plants and their fuel cycles are deployed to generate this 9 GWe from MOX fuel. In the current world situation, plants run either only on UOX fuel (we refer to them as UOX plants) or on a mix of UOX and MOX fuel (we refer to them as MOX plants). The U.S. and Asia rely on UOX plants, whereas Europe and Russia reliesy on a mix of both types. Further, the MOX plants currently have ⅓ of their core loaded with MOX and ⅔ loaded with UOX. Hence the total capacity of these plants is 27 GWe (although of course only 9 GWe is generated from MOX fuel). Figure A-4.7 shows the current fuel cycle with UOX and MOX plants represented separately.

Figure A-4.7 Once-through Cycle with some Plutonium Recycling — 352 GWe Fleet



The total UOX consumption (6,829 MTIHM/yr) is split between the UOX and MOX plants according to UOX-based capacity. Hence, 325/343 of this amount, or 6,471 MTIHM/yr, is required for the UOX plants. The UOX consumption in the MOX plants is therefore 358 MTIHM/yr. A total of 944 MTIHM/yr of spent UOX needs to be reprocessed to produce enough plutonium for MOX fabrication. Therefore, if all the spent UOX from the MOX plants were to be reprocessed (358 MTIHM/yr), 586 MTIHM/yr of spent fuel from the UOX plants must also be reprocessed.

The uranium requirement and waste production can be tabulated according to plant type as follows:

Table A-4.5 Uranium Consumption and Waste Production by Plant Type — Existing 352 GWe Fleet

	U_{nat} feed MT/yr	HLW discharged MT/yr	Pu discharged MT/yr
UOX Plants 325 GWe	66 340	Spent UOX : 6471	Discharged in spent UOX: 86.1
MOX Plants 27 GWe	3 675	Spent MOX: 179.2 Glass: 109 m^3 (48.6 FP, 1.1 MA+Pu) Process Waste : 330 m^3	Consumed for MOX fabrication: 12.6 Discharged in spent MOX: 8.8

Note that all the wastes from reprocessing are assigned to the MOX plants, even though a large fraction of the reprocessed fuel comes from the UOX plants. This is because the reprocessing operations would not be required if it were not for the MOX plants. Note also that the amount of spent fuel from the UOX plants shown in the table (6,471 MTIHM/yr) is the total amount discharged (i.e. including the spent fuel that will be reprocessed). Therefore, the amount of spent fuel from the UOX plants that goes to reprocessing (586 MTIHM/yr) must be subtracted from this number to get the amount of spent UOX that goes to the repository.

Finally, the figures in Table A-4.5 can be expressed on a per GWe basis by dividing the numbers in the first and second rows by 325 GWe and 27 GWe, respectively. This gives an idea of the uranium consumption and waste production for a 1 GWe plant.

Table A-4.6 Uranium Consumption and Waste Production by Plant Type — per GWe

	U_{nat} feed MT/yr	HLW discharged MT/yr	Pu discharged MT/yr
UOX Plants Per GWe	204	Spent UOX : 19.9	Discharged in spent UOX: 265
MOX Plants Per GWe	136 (=2/3·204)	Spent MOX: 6.6 (=1/3·19.9) Glass: 4.0 m^3 (1.8 FP, 0.04 MA+Pu) Process Waste : 12.2 m^3	Consumed for MOX fabrication: 467 Discharged in spent MOX: 327

NOTES

1. Mass of nuclear fuel refers to the mass of the heavy metals present in the fuel. For example, for a fuel consisting of uranium oxide (UO_2) with zirconium cladding, the mass of a given amount of fuel would refer only to the mass of uranium present in the fuel. The mass of the oxygen and of the cladding would not be included.
2. GWd/MTIHM: gigawatt days per metric ton of initial heavy metal; we always refer to the initial mass of heavy metal in the fuel because the heavy metal atoms are fissioned as the fuel is irradiated, and therefore their mass decreases with time.
3. This is the total amount of fuel loaded in the reactors per year. The actual cycle time for US PWRs is now typically 18 months.
4. Xu, Zhiwen, "Design Strategies for Optimizing High Burnup Fuel in Pressurized Water Reactors", MIT doctoral thesis, January 2003. See equation 2.8
5. Xu, Zhiwen, "Design Strategies for Optimizing High Burnup Fuel in Pressurized Water Reactors", MIT Department of Nuclear Engineering doctoral thesis, January 2003. See detailed MCODE results.
6. We of course are neglecting the reduction in the fuel mass discharged due to conversion of mass to energy in the fission process, e.g. a loss of 1.4 MT in this case.
7. Xu, Zhiwen, "Design Strategies for Optimizing High Burnup Fuel in Pressurized Water Reactors", MIT Department of Nuclear Engineering doctoral thesis, January 2003. See detailed MCODE results.
8. The fuel cycle we are considering in this section is not self-generated recycle (SGR). In SGR, all the spent fuel, including the spent MOX, would be reprocessed for plutonium extraction. As of 2002, in all countries using plutonium recycle, the spent MOX fuel is not again reprocessed, in part due to the degraded isotopic composition of plutonium in spent MOX. However, further recycling of plutonium may be carried out in the future.
9. Currently, MOX fuel in LWR is generally irradiated to a burnup lower than 50 GWd/MTIHM, but parity with UOX is anticipated as experience is gained.
10. We assume Pu is mixed with depleted U-238; admixing with natural uranium or spent fuel uranium would provide some U-235 and reduce the Pu requirement slightly.
11. COGEMA, B.BARRE, State of the Art in Nuclear Fuel Reprocessing, SAFEWASTE 2000, October 2000. Values are for the year 2000 (taken from table 3).
12. OECD/NEA, "Plutonium Fuel — An Assessment", 1989. See table 12 B.
13. The question of whether thermal or fast reactors are preferable for burning actinides is still being debated. It should be noted, however, that full actinide recycle in a thermal spectrum is theoretically possible.
14. These values (25% for MA+Pu content and 20% for makeup fraction) are representative of FR burners. For example, see table V (LWR Spent-Fuel Feed) in R.N. Hill, D.C. Wade, J.R. Liaw, and E.K. Fujita, "Physics Studies of Weapons Plutonium Disposition in the the Integral Fast Reactor Closed Fuel Cycle", Nuclear Science and Engineering, 121, 17–31 (1995).
15. World Nuclear Association, "Mixed Oxide Fuel", February 2002, (http://www.world-nuclear.org/info/inf29.htm). This article reports that MOX production reached 190 MTIHM in 2000.

Appendix Chapter 5 — Economics

Appendix 5.A — Calculation of the Levelized Cost of Electricity

The real levelized cost of electricity production is used to assess the economic competitiveness of alternative generating technologies.[1] The real levelized cost of a project is equivalent to the constant dollar ("real") price of electricity that would be necessary over the life of the plant to cover all operating expenses, interest and principal repayment obligations on project debt, taxes and provide an acceptable return to equity investors over the economic life of the project. The real levelized cost of alternative generating technologies with similar operating characteristics (e.g. capacity factors) is a metric used to identify the alternative that is most economical.

A project's real levelized cost can be computed using discounted cash flow analysis, the method employed in the model described below. Revenues and expenses are projected over the life of the project and discounted at rates sufficient to satisfy interest and principal repayment obligations to debt investors and the minimum hurdle rate (cost of equity capital) required by equity investors.

An alternate method, based on traditional regulated utility revenue requirement calculations, is often used to calculate levelized costs for generating technologies. This approach has two problems: First, it fails to account properly for inflation and yields levelized nominal cost numbers that cannot easily be compared across technologies with different capital intensities. Second, it imposes a particular capital cost repayment profile that, while consistent with the way regulated investments were treated, is not consistent with the merchant generation investment environment that now characterizes the U.S., Western Europe and a growing number of other countries.

The spreadsheet model used to calculate real levelized costs for nuclear, coal, and natural gas-fired power plants is described in the following sections. Table A-5.A.1 defines variables used throughout the appendix. The cash flows are first generated in nominal dollars in order to calculate income taxes properly and then adjusted to constant real prices using the assumed general inflation rate (3% in the examples below).

Table A-5.A.1 Model Variables

C_O	Overnight cost (\$/kWe)	HR	Heat rate (BTU/kWh)
T_C	Construction time (years)	C_{Fuel}	Unit cost of fuel (\$/mmBTU)
C_{TOT}	Total construction cost (\$/kWe)	C_{Waste}	Nuclear waste fee (mills/kWh)
D/V	Debt fraction of initial investment	C_{OMf}	Fixed O&M (\$/kWe/yr)
E/V	Equity fraction of initial investment	C_{OMv}	Variable O&M (mills/kWh)
r_D	Nominal cost of debt	C_{Incr}	Incremental capital costs (\$/kWe/yr)
r_E	Nominal cost of equity	C_{Decom}	Decommissioning cost (\$million)
N	Plant life (years)	τ_{Carbon}	Carbon emissions tax (\$/tonne-C)
L	Plant net capacity (MWe)	I_{Carbon}	Carbon intensity of fuel (kg-C/mmBTU)
Φ	Capacity factor	R_n	Revenues in period n
p_n	Nominal price of electricity in period n	I_n	Interest payment in period n
τ	Marginal composite corporate income tax rate	$C_{n,Op}$	Total operating expenses in period n

CAPITAL INVESTMENT

Power plants require significant capital investments before electricity production can begin. The cash flow model allocates the overnight cost of the plant, C_O, specified in \$/kWe of the year production begins (2002), over the construction period, T_C, allowing for an additional period after construction for final licensing and testing. By convention, all investment expenditures are counted at the beginning of the year in which they occur, and all revenues and operating expenses are assumed to occur at the end of the year. Numerous construction expenditure profiles are available in the model, including a uniform profile and one that peaks at mid-construction, characterized by a sinusoidal function. The annual capital expenditures for the nuclear plant costing \$2,000/kWe in base year prices (2002) and a combined-cycle gas turbine (CCGT) plant costing \$500/kWe are presented in Table A-5.A.2.

Table A-5.A.2 Representative Construction Outlays (nominal dollars)

YEAR	- 5 $/kWe	- 4 $/kWe	- 3 $/kWe	- 2 $/kWe	- 1 $/kWe	TOTAL OUTLAY (mixed $/kWe)	OVERNIGHT COST (2002 $/kWe)	TOTAL COST (2002 $/kWe)
Nuclear	165	444	566	471	185	1,831	2,000	2,557
CCGT	0	0	0	236	243	478	500	549

Nuclear: 5 year construction period, sinusoidal profile, i = 3%
CCGT: 2 year construction period, uniform profile, i = 3%

Note that the overnight cost is specified in constant dollars of the year production begins (year 2002 \$), and so the capital expenditure in each year is deflated to current-year (nominal) dollars. This explains why the total outlay in nominal dollars is numerically smaller than the overnight cost.

$$X_n = F_n C_O\,(1 + i)^n$$

where X_n is the outlay in year n (n = 0 in 2002, n < 0 during construction), F_n is the fraction of the overnight cost allocated to year *n*, and *i* is the rate of general inflation. In order to finance construction, the project takes on debt obligations and attracts equity investors with certain requirements. Debt and equity each have an expected minimum rate of return and debt has a specified repayment period. The interest on debt and imputed interest on equity are added to the overnight cost to find the total cost of construction.

$$C_{TOT} = \sum_{n<0} X_j\,(1 + r_{eff})^{-n} \qquad r_{eff} = \frac{D}{V} r_D + \frac{E}{V} r_E$$

employing an effective interest rate r(eff). The total cost of construction does not represent true cash flows but is a measure of construction cost taking into account the time value of money. The total costs in the Table A-5.A.2 correspond to 50/50 debt/equity, $r_D = 8\%$, $r_E = 15\%$ for the nuclear case ($r_{eff} = 11.5\%$) and 60/40 debt/equity, $r_D = 8\%$, $r_E = 12\%$ for the CCGT case ($r_{eff} = 9.6\%$).

ASSET DEPRECIATION

Once put in service, the power plant depreciates according to a specified schedule. The treatment of depreciation is important in the calculation of the annual tax liability, since asset depreciation is a tax-deductible expense. In the base case model we use accelerated depreciation, based on Modified Accelerated Cost Recovery System (MACRS) guidelines, assuming a 15 year asset life. The total capital expenditure (excluding interest and equity appreciation) during construction is used as the depreciable asset base. The depreciable asset base is based on nominal rather than real expenditures. So, for example, if the base year overnight construction cost is $2,000/kW and inflation is 3% per year, the depreciable asset base will be less than the overnight cost in base year prices, to reflect the fact that actual expenditures will be made during earlier years with lower nominal prices.

REVENUES

The sole source of revenue for the power plant is the sale of electricity. The price of electricity in 2002 is determined in an iterative process such that required returns to investors are met. This price, *p*, is equivalent to the levelized cost of the plant. In order to represent a real levelized cost, the price of electricity escalates at the rate of general inflation.

Annual revenue is the product of the quantity of electricity produced and its price. The plant's net capacity and capacity factor determine the annual electric generation.

$$Q = \frac{L}{10^3} \cdot \Phi \cdot 8{,}760 \, \frac{hours}{year} \quad (GWh/year)$$

$$R_n = Qp_n \quad p_n = p_n \, (1 + i)^n$$

where the rated capacity, *L*, is specified in MWe. A 1,000 MWe plant with an annual capacity factor of 85% produces 7,446 GWh of electricity per year.

OPERATING EXPENSES

Operating expenses are incurred throughout the operational life of the plant and include fuel, operating and maintenance costs, and decommissioning funds. Carbon emissions taxes and incremental capital expenditures similarly are treated as operating expenses. (Treating incremental capital expenditures as operating expenses instead of additions to the depreciable asset base is a simplification to avoid having to specify additional depreciation schedules. Because expenditures are assumed to occur every year, the error introduced is small.) Non-fuel operating expenses can be broken down into fixed and variable cost components and are generally assumed to increase at the rate of inflation, though in some cases a real escalation rate is included. The assumed escalation of real fuel prices is a variable input to the model. This is particularly useful in the CCGT case where increases in natural gas prices have a large impact on the levelized cost of generation. Table A-5.A.3 lists the plant's operating expenses along with their arithmetic expressions.

Table A-5.A.3 Operating Expenses

EXPENSE	VALUE IN YEAR n ($million)	NOTATION
Fuel	$\frac{C_{Fuel}}{10^6} \cdot HR \cdot Q \cdot (1+e_f)^n$	$C_{n,\ fuel}$
Waste fund[a]	$\frac{C_{Waste}}{10^3} \cdot Q \cdot (1+i)^n$	$C_{n,\ waste}$
Fixed O&M	$C_{OMf} \cdot \frac{L}{10^6} \cdot (1+e_{om})^n$	$C_{n,\ omf}$
Variable O&M	$\frac{C_{OMv}}{10^6} \cdot Q \cdot (1+e_{om})^n$	$C_{n,\ omv}$
Decommissioning[a, b]	$C_{Decom} \cdot (1+i)^N \cdot SFF_0$	$C_{n,\ decom}$
Incremental capital	$C_{Incr} \frac{L}{10^3} \cdot (1+i)^n$	$C_{n,\ incr}$
Carbon emissions tax	$\frac{\tau_{Carbon}\ I_{Carbon}}{10^9} \cdot HR \cdot Q \cdot (1+i)^n$	$C_{n,\ carbon}$

a. Specific to nuclear plants
b. SFF_0 is the sinking fund factor for N years at the risk free rate.

Total operating expenses are:

$$C_{n,Op} + C_{n,fuel} + C_{n,waste} + C_{n,omf} + C_{n,omv} + C_{n,decom} \quad \$million$$

Total operating expenses, $C_{n,\ op}$, incremental capital expenditures, and carbon emissions taxes are subtracted from revenues before computing the annual tax liability. Two other adjustments are made to taxable income. Asset depreciation, D_n, and interest payments I_n to creditors are both treated as tax-deductible expenses and thus reduce taxable income. The tax liability, T_n, is simply the product of taxable income and the composite marginal corporate income tax rate,, assumed to be 38% in the base cases.[2]

$$T_n = \tau\left[R_n - C_{n,Op} - C_{n,incr} - C_{n,carbon} - D_n - I_n\right]$$

A production tax credit is available in the model to simulate, along with the carbon emissions tax, public policies to curb CO_2 emissions.

INVESTOR RETURNS

The model solves for a constant real price of electricity sufficient to provide adequate returns to both debt and equity investors.[3] Interest on debt accrues during construction and is repaid with the principal in equal annual payments over the specified term of the debt. Equity holders invest funds during construction and receive profits net of taxes and debt obligations during plant operation. Net profits over the life of the project are such that the internal rate of return (IRR) of the equity holders' cash flows equals the required nominal return; 15% in the nuclear base case and 12% in the fossil cases. The model includes a constraint that the debt payment obligations specified are made in full each year (the project is not allowed to default on debt obligations). For example, assume that the

Table A-5.A.4 Base Case Input Parameters

YEAR	NUCLEAR	COAL	NGCC
Inflation rate	3%	3%	3%
Interest rate	8%	8%	8%
Expected return to equity investor	15%	12%	12%
Debt fraction	50%	60%	60%
Tax rate	38%	38%	38%
Debt term	10 years	10 years	10 years
Net capacity	1,000 MWe	1,000 MWe	1,000 Mwe
Capacity factor	85%	85%	85%
Plant life	40 years	40 years	40 years
Heat rate	10,400	9,300	7,200
Overnight cost	$2,000/kWe	$1,300/kWe	$500/kWe
Construction period	5 years	4 years	2 years
Post-construction period	—	—	—
Depreciation schedule	Accelerated, 15 years	Accelerated, 15 years	Accelerated, 15 years
Decommissioning cost	$350 million	—	—
Incremental capital costs	$20/kWe/yr	$15/kWe/yr	$6/kWe/yr
Fuel costs	$0.47/mmBTU	$1.20/mmBTU	$3.50/mmBTU
Real fuel escalation	0.5%	0.5%	1.5%
Nuclear waste fee	1 mill/kWh	—	—
Fixed O&M	$63/kWe/yr	$23/kWe/yr	$16/kWe/yr
Variable O&M	0.47 mills/kWh	3.38 mills/kWh	0.52 mills/kWh
O&M real escalation rate	1.0%	1.0%	1.0%
Carbon intensity	—	25.8 kg-C/mmBTU	14.5 kg-C/mmBTU
Carbon tax	—	—	—

Note: Compiled from public information, including reports from the Energy Information Administration.

model solves for a constant real price of electricity that satisfies the return required by equity holders. In most cases, the solution would be deemed the levelized cost of electricity. However, if the resultant operating income (revenues less operating expenses) is insufficient to cover the entire debt payment in any year, the electricity price is raised until all debt payments can be made. If the debt service constraint is binding, the realized return on equity will then exceed the minimum required return specified.

Since the purpose of the levelized cost calculation is to compare alternative generating technologies and assess their potential contribution to future energy supply, the technologies compared must generate electricity over equivalent time periods. In order to maintain the level basis for comparison, plants are not allowed to shut down prematurely when operating expenses exceed revenues, as in the case of escalating natural gas prices. The result in these situations is a cash flow stream for the project that does not reflect expected business decisions. Nonetheless, for comparison of future electricity supply options, it is more appropriate to include the effect of high natural gas prices in the out years than to exclude it by running the plant shorter than its projected life. In this case, the plant must still meet all debt obligations and a minimum return on investment to equity investors.

Table A-5.A.5 Nuclear Base Case Cash Flows (nominal dollars)

YEAR	1	2	3	5	10	20	30	40
Electricity price (cents/kWh)	6.91	7.12	7.33	7.78	9.02	12.12	16.28	21.88
Revenue ($million)	515	530	546	579	672	903	1,213	1,631
Operating expenses ($million)								
- Fuel cost	38	39	40	43	51	73	103	145
- Waste fee	8	8	8	9	10	13	18	24
- Fixed O&M	66	68	71	77	94	139	206	306
- Variable O&M	4	4	4	4	5	8	11	17
- Decommissioning	9	9	9	9	9	9	9	9
- Incremental cap.	21	21	22	23	27	36	49	65
Operating income	370	381	391	414	475	625	817	1,063
Depreciation (tax)	92	174	157	127	108	0	0	0
Interest payments	92	86	79	64	13	0	0	0
Debt principal repayment	80	86	93	108	159	0	0	0
Taxable income	186	121	156	223	354	625	817	1,063
Income tax payment	71	46	59	85	135	237	310	404
Net profit	127	163	160	157	169	387	506	659

Table A-5.A.6 CCGT Base Case Cash Flows (nominal dollars)

YEAR	1	2	3	5	10	20	30	40
Elec. price (cents/kWh)	4.25	4.38	4.51	4.78	5.54	7.45	10.01	13.45
Revenue ($million)	317	326	336	356	413	555	746	1,003
Operating expenses ($million)								
- Fuel cost	196	205	215	234	293	457	712	1,111
- Waste fee	—	—	—	—	—	—	—	—
- Fixed O&M	16	17	18	19	23	34	51	76
- Variable O&M	4	4	4	5	6	9	13	19
- Decommissioning	—	—	—	—	—	—	—	—
- Incremental cap.	6	6	7	7	8	11	15	20
Operating income	94	93	93	91	83	45	-45[a]	-223[a]
Depreciation (tax)	24	45	41	33	28	0	0	0
Interest payments	26	24	22	18	4	0	0	0
Debt principal repayment	22	24	26	30	44	0	0	0
Taxable income	44	24	30	40	51	45	0	0
Income tax payment	17	9	11	15	20	17	0	0
Net profit	29	36	33	28	16	28	-45[a]	-223[a]

a. For the purposes of comparing energy supply options, plant operation is not terminated when operating costs exceed revenues.

Appendix 5.B – Nuclear Power Plant Construction Costs

This section contains a summary of available information on nuclear power plant construction costs. The information includes construction cost estimates by government and industry sources, actual cost data from recent experience abroad, and some recent indications of the current market valuation of nuclear plants. The data are somewhat sparse but are helpful in determining what nuclear plants cost to build now, what they are projected to cost in the future, and what cost will make nuclear viable in a competitive electricity generation market. Cost figures are presented in a variety of formats (overnight costs, total construction costs, levelized costs) in the sources cited and are generally presented in the format given by the source.

CONSTRUCTION COST FORECASTS

EIA — Annual Energy Outlook 2003[4]

Cost and performance characteristics for nuclear plants in the Annual Energy Outlook are based on current estimates by government and industry analysis. Two cost cases are analyzed, the reference case and an advanced nuclear cost case, where overnight costs are reduced to be consistent with the goals endorsed by DOE's Office of Nuclear Energy.

In the reference case, overnight construction costs are predicted to be $2,044/kWe in 2010 and $1,906/kWe in 2025, specified in 2001 dollars. Construction costs are assumed to decline over time based on a representative learning curve. The overnight costs reported include a 10% project contingency factor and a 10% technological optimism factor, which is applied to the first four units to reflect the tendency to underestimate costs for a first-of-a-kind unit. The report indicates a five year lead time for construction. Predicted overnight costs for the advanced nuclear case are $1,535/kWe in 2010, dropping to $1,228/kWe by 2025, also reported in 2001 dollars. The advanced case does not include a technological optimism factor.

DOE-NE — 2010 Roadmap Study[5]

The economic analysis in the 2010 Roadmap study takes a parametric approach to nuclear capital costs, but states that engineering, procurement, and construction costs vary between $800 and $1,400 / kWe. Adding 20 percent for owner's costs and project contingency, the approximate range for overnight costs is $1,000–$1,600 / kWe in 2000 dollars. Construction is assumed to occur over 42 months, with six months between construction and commercial operation.

In addition to the parametric analysis, the 2010 Roadmap study evaluated eight advanced nuclear plant designs as candidates for near term deployment. The cost estimates for the new designs were provided by vendors with various levels of confidence and detail. A brief summary of relevant information for the eight designs is tabulated in Table A-5.B.1.

Table A-5.B.1

DESIGN	OVERNIGHT COST	OTHER RELEVANT INFORMATION
GE ABWR	\$1,400–\$1,600/kWe	48 month construction (Japan) Real construction experience
GE ESBWR	Lower than ABWR	Availability goal of 92% Simplified design to reduce cost
Framatome SWR-1000	\$1,150–\$1,270/kWe FOAK[a] 15-20% reduction for NOAK[b]	Cost excludes cooling tower 48 month construction, 91% avail.
Westinghouse AP600	\$2,175/kWe FOAK \$1,657/kWe NOAK	5 years from order placement to commercial operation
Westinghouse AP1000	\$1,365/kWe FOAK \$1,040/kWe NOAK	Cost assumes twin units, includes owner's costs and contingency
Westinghouse IRIS	\$687–\$1,224/kWe FOAK \$746–\$1,343/kWe NOAK	100-300 MWe plant availability 85-99%
Pebble Bed Modular Reactor	\$1,250/kWe NOAK	110 MW units
General Atomics GT-MHR	\$1,122/kWe 25% reduction for NOAK	Cost includes contingency and owner's costs

a. FOAK - First-of-a-kind
b. NOAK - Nth-of-a-kind

NEA/IEA — Projected Costs of Generating Electricity[6]

The estimates of construction and operating costs for power plants contained within the NEA/IEA report are compiled from OECD countries and are based on a combination of engineering estimates, paper analyses, and industry experience. The authors decompose the cost submissions and recompile them using standard assumptions and two real discount rates, 5% and 10%. Not every country includes the same cost items in its totals, making comparisons across countries difficult, and all costs are converted to US dollars using a spot exchange rate. Cost estimates are listed for the United States and for the entire OECD range. (See Table A-5.B.2.) Costs for closed fuel cycles are not included in the range of estimates. The costs reported in the NEA/IEA report are identical to those in the NEA report *Nuclear Power in the OECD*, published in 2001.

Table A-5.B.2

PARAMETER	UNITED STATES	OECD
Base year for costs	1996	1996
Capacity factor	75%	75%
Overnight cost[a]	\$1,585 / kWe	\$1,585 – \$2,369 / kWe
Overnight cost (2002 dollars)	\$1,831 / kWe	\$1,831 – \$2,737 / kWe
Total construction cost (2002 dollars)	\$2,139 / kWe	\$2,139 – \$3,101 / kWe
Construction period	4 years	4 – 9 years

a. Includes owner's costs and a contingency factor.

Finland

The Finnish parliament in May 2002 approved construction of a new nuclear power plant by the electric utility Teollisuuden Voima Oy (TVO), based in part on the economic analysis of generation options by Risto Tarjanne of the Lappeenranta University of Technology, Finland.[7] A fifth nuclear unit is seen as the superior generation choice to limit imports of Russian natural gas, allow Finland to meet Kyoto Protocol commitments, and guarantee cheap electric power to the Finnish industry. It is important to note that TVO is a non-profit company that provides electricity to its industrial shareholders at cost, effectively providing a long-term power purchase agreement not likely available to plant owners in a competitive environment.

The economic analysis supporting the decision to build a fifth nuclear reactor compares the economics of a new nuclear plant to a pulverized coal plant, a combined-cycle gas turbine plant, and a peat-fired plant. Low nuclear construction and operating costs, high plant performance, and a 5% real discount rate contributed to nuclear power being the superior choice. The study assumed an initial nuclear investment cost of 1,749 euros/kWe, including interest during construction, and a five year construction period. Using an exchange rate of 1.0 euro / U.S. dollar and inflating to 2002 dollars, the total construction cost used in the analysis is roughly $1,830/kWe, implying an overnight cost of about $1,600/kWe. [8]

UK Energy Review

The UK Performance and Innovation Unit's Energy Review addresses the construction cost of nuclear plants by evaluating submitted estimates from British Energy and BNFL.[9] The report first notes that the construction cost for Sizewell B, completed in 1994, was £3,000/kWe in 2000 money ($US 5,000/kWe at current exchange rates), including first- of-a-kind (FOAK) costs (£2,250/kW excluding FOAK costs or $US3,700/kWe at current exchange rates), for a total cost of generation around 6p/kWh or 9.6 ¢US/kWh at current exchange rates (excluding FOAK costs). Industry (British Energy and BNFL) now predicts that the Westinghouse AP1000 could generate electricity at 2.2-3.0 p/kWh or 3.3 to 4.8 ¢US/kWh ignoring FOAK costs. The construction costs assumed in these estimates were considered commercially confidential and were not included in the report. The PIU report notes that the construction costs provided by the industry were better than the best recent estimates from OECD countries,[10] and that operating availability estimates were questionably high. The PIU analysis suggests a range of 3p/kWh to 4p/kWh (or 4.8 to 6.4 ¢US/kWh for future nuclear cost of generation, consistent with total construction costs of roughly £1,400–1,700/kWe in 2000 money, or about $2,300–$2,900/kWe at current exchange rates.

RECENT MARKET VALUATION OF NUCLEAR PLANTS

Sale of Seabrook Nuclear Station – 2002

In 2002, 88.2% ownership of Seabrook Nuclear Station (1,024 MWe) was transferred to Florida Power & Light through a competitive auction process. The sale price was $749.1 million for the operating plant ($730/kWe), plus $25.6 million for components from an uncompleted unit and $61.9 million for nuclear fuel. The deal included no power purchase agreement. FP&L will receive the current balance of the decommissioning trust fund, estimated at $232.7 million. The NRC operating license for Seabrook is set to expire in October 2026, allowing for more than 20 years of service with the possibility of a 20-year license extension. This implies that the market value of a fully licensed and operating nuclear power plant with a good performance record is less than half of the most optimistic cost estimates for building a new nuclear power plant and only about 30% more than the cost of CCGTs being built in New England during this time period. This in turn implies that merchant investors in nuclear power plants believe either (a) that future operating costs are much higher than is assumed in engineering cost studies or (b) that the commercial risks associated with even a licensed and operating plant are so high that a very high cost of capital is imputed to future cash flows, or a combination of both. Comparable analyses of other recent nuclear power plant sales come to very similar conclusions. The market value of nuclear plants is far below their replacement cost, a result that is inconsistent with merchant investment in new nuclear plants.

Browns Ferry Unit 1 Restart – TVA

In May 2002, the TVA board of directors approved a plan to restart Browns Ferry Nuclear Unit 1, idle since 1985. The decision was based on recent improvements in nuclear operating performance and costs at TVA plants and a reduced estimate of the cost to restart the unit. The analysis tiered from Energy Vision 2020, TVA's resource integration plan, which in 1995 recommended deferring a decision on Browns Ferry Unit 1 until more data could be collected on operating performance and costs. Browns Ferry Unit 1 has an active NRC operating license that will expire in 2013, but TVA plans to apply for a 20-year license extension if the unit is recovered.

The new analysis estimates that the restart of BFN Unit 1 will cost between $1.56 and $1.72 billion in 2002 dollars and will take 5 years to complete.[11] This corresponds to an overnight capital cost of about $1,280/kWe. The 2002 TVA report indicates that the levelized cost of the project will be less than that of an alternative natural gas-fired combined cycle plant, based on a financial research report quoting the levelized cost of a combined cycle plant as $51.00/MWh.[12]

The crucial factors that makes nuclear competitive in this case are (a) that the expenditures are required to upgrade an existing plant that already has significant capital facilities in place and (b) TVA's assumed low cost of capital. The restart will be financed entirely with debt, TVA is able to borrow money very cheaply, and the company doesn't pay federal income taxes or local property and sales taxes.[13] Coupling their low cost of capital with recent experience of high performance and low operating costs, nuclear appears to be the low-cost option.

RECENT NUCLEAR CONSTRUCTION ABROAD

A few countries are actively building nuclear plants using new nuclear designs and advanced construction techniques to which estimated cost reductions are attributed. Unfortunately, actual cost data for these projects is difficult to acquire. Project costs for newly operating plants in Japan and South Korea are discussed in this section and should provide some evidence as to whether projected cost reductions are being realized.

It is important to note the difficulty in comparing costs of construction projects across countries. Differences in the relative costs of local resources and construction technologies, government regulations, labor productivity, and the fact that a large fraction of nuclear plant costs depend on local labor and construction resources and are not tradeable across countries are such that the costs of construction projects in different countries must be compared with great care. Currency exchange rates may not accurately reflect the relative costs of goods and services that are not traded internationally, and are susceptible to rapid fluctuations that obscure real costs.[14] An alternative approach to international comparison is the use of purchasing power parities (PPP) that adjust for price level differences between countries and thus attempt to equalize the purchasing power of different currencies. The Japanese and Korean construction cost data below are interpreted using PPPs compiled by the OECD and Eurostat for gross fixed capital formation, including construction, machinery, and equipment.[15] The PPPs are assembled every three years based on prices of representative goods, services, and projects, provided by participating countries. The use of PPPs for international comparisons of construction projects does not resolve all regional differences, but is generally expected to be more consistent and perhaps more accurate than using current exchange rates alone.

Japanese Nuclear Plant Construction

Japan is one of the few countries actively building nuclear plants at this time.

Construction costs for recent nuclear plants by Tohoku and Kyusyu utilities were compiled for us by a Japanese analyst from public information and are tabulated below.

Table A-5.B.3

OWNER	NAME OF PLANT	CAPACITY	COMMERCIAL OPERATION DATE	TOTAL PROJECT COST (109 YEN)	U.S. EQUIVALENT[a]
Tohoku Electric	Onagawa 3 (BWR)	825 MWe	January 2002	314	$2,409/kWe
Kyusyu Electric	Genkai 3 (PWR)	1,180 MWe	March 1994	399	$2,818/kWe
	Genkai 4 (PWR)	1,180 MWe	July 1997	324	$2,288/kWe

Note: Compiled from public information by the MIT Center for Energy and Environmental Policy Research.
a: Using PPP of 158 yen / U.S. dollar.

Recent data for BWR plants built for Tokyo Electric Power Company (TEPCO) at its Kashiwazaki-Kariwa Nuclear Power Station is given next. Units 3 and 4, both 1,000 MWe BWR designs, were completed in 1993 and 1994 respectively. More interesting for our purposes, units 6 and 7, GE 1,356 MWe ABWR designs, were completed in 1996 and 1997. Approximate costs of constructing the reactors come from multiple sources, all of which give values within a modest range of each other: TEPCO annual reports, publicly available data on reactor costs from TEPCO, and direct communications with TEPCO.

Data contained in TEPCO's Annual Reports were analyzed as follows. Incremental capital costs were estimated based on the average increase in nuclear asset values in years in which reactors were not added to the asset base. This quick approach resulted in incremental capital costs on the order of current data in the United States. Subtracting incremental capital costs from the annual increase in nuclear assets produced an estimate of the construction cost for each plant in the year it began construction. Several factors may skew the construction cost estimate, but they are not seen as significant within the scope of the study. Estimates of interest during construction in Japan during this time period are low, and so whether or not it is capitalized and included in the asset balance will have only a minor effect. Inflation was ignored, as it has been low in Japan over this period as well. The annual reports yielded construction costs of 320-340 billion yen each for units 3 and 4, and 400-420 billion yen each for units 6 and 7. Using a PPP of 158 yen / U.S. dollar,[16] construction costs were equivalent to $US1,800–$US2,000/kWe for the ABWR units.

TEPCO presents rough figures for construction costs of each plant on its website. The approximate costs presented are 325 billion yen for Kashiwazaki-Kariwa (KK) 3, 334 billion yen for KK4, 418 billion yen for KK6, and 367 billion yen for KK7. These values are close to those derived from the annual reports, with the exception of KK7 at $1,710/kWe, using the same PPP as above. Information compiled for us by a Japanese analyst from public information confirms these estimates: 433 billion yen for KK6 ($2,020/kWe) and 384 billion yen for KK7 ($1,790/kWe).

Korean Nuclear Plant Construction

South Korea possesses 18 operating nuclear reactors with two more planned to connect to the grid in 2004/2005. The latest reactors, Yonggwang 5 & 6, are 1,000 MWe PWRs, using the Korean Standard Nuclear Power Plant (KSNP) design, based on the Combustion Engineering System 80. The Yonggwang plant is owned and operated by Korea Hydro & Nuclear Power, a subsidiary of Korea Electric Power (KEPCO). KEPCO is a state-run monopoly that is in the process of privatizing its power generation business. The construction was financed through debt.

Construction of the two reactors cost an estimated 3.91 trillion Korean won. The overnight cost is estimated at 3.11 trillion won at 2002 price levels.[17] Using a PPP of 867 won / U.S. dollar,[18] the unit overnight cost is equivalent to about $1,800 / kWe and the total construction cost is equivalent to about $2,300 / kWe. Care should be taken when attempting to apply these cost figures to construction in other parts of the world, because the challenges of international comparisons discussed above become more significant when developing countries are being considered.

Appendix 5.C — Nuclear Power Plant Operating Costs

Nuclear power plant operating costs are generally assumed to be more predictable than those of fossil plants, due to relatively stable fuel prices. This appendix presents several estimates of historical operating costs and projections of future costs for nuclear plants. The focus is on non-fuel operating and maintenance (O&M) costs. Some sources record non-fuel operating costs while others include the cost of fuel. For purposes of comparison, nuclear fuel costs can be assumed to be in the range of 5-6 mills/kWh.

Recent performance of nuclear plants indicates that *non-fuel* O&M costs averaged between 12 and 18 mills/kWh. Costs for the best plants have been below 8 mills/kWh while costs for the worst plants have exceeded 25 mills/kWh. Projections of future costs tend toward the low end of this range and below, with some projections as low as 5 mills/kWh for non-fuel O&M.

EIA — ELECTRIC POWER ANNUAL 2001

The Energy Information Administration (EIA) reports average operating costs for major U.S. investor-owned electric utilities in its *Electric Power Annual.*[19] The current Annual reports average operating costs for the period 1990–2001, based on utility filings of FERC Form 1, *Annual Report of Major Electric Utilities, Licensees, and Others.* Non-fuel O&M costs for nuclear plants averaged 18 mills/kWh, adjusted to 2002 dollars, for the period 1990–2001, and have declined in each of the past five years. For the five year period ending in 2001, non-fuel O&M costs averaged 16 mills/kWh and the average has dropped to 14 mills/kWh since 2000. For comparison, fossil steam plant O&M costs averaged around 6 mills/kWh for the 12 year period, excluding fuel costs.

Table A-5.C.1 Nuclear Power Plant Operating Costs, 1990–2001

(mills/kWh)	1999	2000	2001	1990–2001 AVERAGE	1997–2001 AVERAGE
Non-fuel O&M	14.1	13.3	13.3	15.3	14.9
- 2002 dollars	**15.2**	**14.0**	**13.6**	**18.1**	**16.1**
Fuel costs	5.2	5.0	4.7	5.7	5.1
Total operating costs	19.2	18.3	18.0	21.0	20.0

Source: EIA, Electric Power Annual 2001

EIA — NUCLEAR POWER PLANT OPERATING COSTS

The EIA report, *An Analysis of Nuclear Power Plant Operating Costs: A 1995 Update,*[20] provides more detailed information on nuclear plant operating costs, though the analysis is limited to pre-1994 data. As in the *Electric Power Annual,* utility data are collected from FERC Form 1 filings and historical trends in operating costs are analyzed. Between 1974 and 1984, real non-fuel O&M costs escalated at an annual rate of 12%, and increased regulatory action was cited as the major factor causing the cost escalation. Over the last five years of the sample period (1989–1993), O&M costs escalated by less than 1% annually, with a cost of $96/kW in 1993 (equivalent to 13 mills/kWh for 85% capacity factor).

The 1995 report offers a number of interesting statistics about nuclear O&M costs. First, the report lists O&M costs for individual plants over the last four years. From these data, it can be seen that O&M costs for the best performer are just over half (56%) of the average costs across the fleet. Costs for the lowest cost quartile are 20% below average, 16% above average for the highest cost quartile, and 86% above average for the worst performer.

Second, a regression analysis determines that plant aging, NRC regulatory activity, and regulatory incentives to improve performance were the three most important factors influencing changes in O&M costs over time.[21] It is estimated that 67% of the reported O&M costs are labor related, with the remaining 33% for expenditures on maintenance materials and supplies.

Third, and most important for assessing the total cost of nuclear generation, the report lists cost items that are not included in the reported O&M costs. Insurance premiums for property damage, third-party damages, and replacement power in case of an accident are not included. Additionally, NRC regulatory fees and some payroll taxes and fringe benefits are not included because they are reported in aggregate for the utility. A study performed by Oak Ridge National Laboratory estimated that the reported O&M costs understate the actual costs by up to 30%.[22]

NUCLEAR ENERGY INSTITUTE (NEI)

NEI presents 3-year rolling average production costs for U.S. nuclear plants based on data from the Utility Data Institute and the Electric Utility Cost Group.[23] The table shows consistent cost reductions across the fleet. The fleet average production cost for 1998–2000 was 17.4 mills/kWh, including fuel costs. However, the lowest cost quartile achieved total O&M costs of about 13 mills/kWh and the second lowest cost quartile 15 mills/kWh.

Table A-5.C.2 3-year Rolling Average O&M Costs for U.S. Nuclear Plants

(mills/kWh)	1st QUARTILE	2nd QUARTILE	3rd QUARTILE	4th QUARTILE
1996–1998	14.3	16.9	20.4	38.8
1997–1999	13.3	15.8	18.4	28.0
1998–2000	12.7	15.0	17.3	24.6

OPERATING COST PROJECTIONS

The most recent projections from EIA are for fixed nuclear O&M costs of $58/kW and variable O&M costs of 0.43 mills/kWh.[24] Assuming an 85% average capacity factor, this is equivalent to 8 mills/kWh (excluding fuel). The economic analysis in the Department of Energy 2010 Roadmap study pushes operating costs down further by projecting non- fuel O&M costs around 5 mills/kWh for near term deployment plants.[25] The report notes that this is in line with the best currently operating plants. And TVA, in its evaluation of the proposed restart of Browns Ferry Unit 1, projects O&M costs below 8 mills/kWh, based on recent experience at its other nuclear facilities. These operating cost projections are significantly below the actual operating cost numbers drawn from recent experience displayed above.

Appendix Chapter 5.D — Costs of Reprocessing

Spent UOX fuel typically contains a little over 1% Pu. Through reprocessing (PUREX process), it is possible to recover this plutonium and use it to make MOX fuel for use in LWRs. However, because of the high costs of reprocessing and of MOX fuel fabrication, the cost of repository disposal must be very high in order for the MOX option to become economically competitive with the once-through UOX cycle. We support this conclusion with the following analysis.

Fuel Cycle Cost Model — A simple expression for the fuel cycle cost is as follows:

$$FCC = \sum_i M_i \cdot C_i + \sum M_i \cdot C_i \cdot \phi \cdot \Delta T_i \quad [\$]$$

where:

FCC = Fuel Cycle Cost [$]

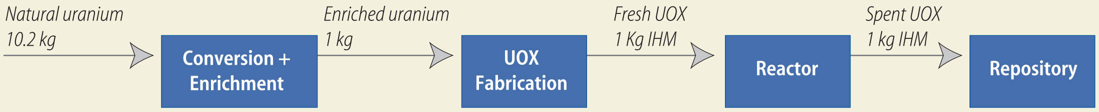
M_i = mass processed at stage i [kg or kg SWU]

C_i = unit cost at stage i [$/kg or $/kg SWU]

ϕ = carrying charge factor (yr^{-1})

ΔT_i = delay between the investment for stage i and the midpoint of the irradiation of the fuel (years)[26]

UOX cycle — The once-through UOX cycle is represented below (for 1 kgIHM[27] of fuel):



Assumptions

- U235 content of natural U: 0.711%
- Enrichment tails assay: 0.3%
- Fresh fuel enrichment: 4.5%
- Losses are neglected
- Burnup: 50 MWD/kgHM
- Capacity factor: 0.9
- Thermal efficiency: 0.33

The Separative work per unit of enriched product can be obtained as:[28]

$$\frac{\text{kg SWU}}{\text{kg product}} = (2x_p - 1) \cdot \ln\left(\frac{x_p}{1 - x_p}\right) + \frac{x_p - x_{nat}}{x_{nat} - x_t} \cdot (2x_t - 1) \cdot \ln\left(\frac{x_t}{1 - x_t}\right) - \frac{x_p - x_t}{x_{nat} - x_t} \cdot (2x_{nat} - 1) \cdot \ln\left(\frac{x_{nat}}{1 - x_{nat}}\right)$$

where:

x_p = product enrichment

x_{nat} = natural enrichment

x_t = tails assay

Using the values presented above for x_p, x_{nat}, and x_t, we get 6.23 kg SWU/kg product.[29]

The fuel cycle cost can now be calculated (for 1 kgIHM of fresh UOX fuel):

Table A-5.D.1 Once-through UOX Fuel Cycle Cost

	M_i	C_i	ΔT_i (yr)	DIRECT COST $M_i \cdot C_i$ (\$)	CARRYING CHARGE $M_i \cdot C_i \cdot \phi \cdot \Delta T_i$ (\$)
Ore purchase	10.2 kg	30 $/kg	4.25	307	130
Conversion	10.2 kg	8 $/kg	4.25	82	35
Enrichment	6.23 kg SWU	100 $/kg SWU	3.25	623	202
Fabrication	1 kgIHM	275 $/kgIHM	2.75	275	76
Storage and disposal	1 kgIHM	400 $/kgIHM[30, a]	–2.25	400	-90
			Total	1686	353
			Grand Total	2040	

a. The cost of waste storage and disposal is assumed to be paid at the end of irradiation, even though the unit cost of $400/kgIHM is a proxy for the 1 mill/kWehr paid by utilities during irradiation.

The calculations are based on the following assumptions:

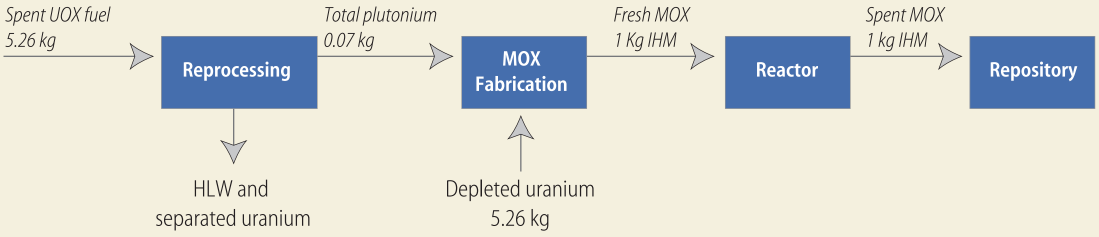
- Fuel irradiation time : 4.5 years
- Lead times:
  - 2 years for ore purchase
  - 2 years for conversion
  - 1 year for enrichment
  - 0.5 year for fuel fabrication
- Carrying charge factor: $\phi = 0.1$ per year.

The cost is thus $2,040/kgIHM. We can obtain the fuel cycle cost in ¢/kWh(e) as follows:

$$\frac{kgIHM}{0MWd} \cdot \frac{1MW}{1000kW} \cdot \frac{1d}{24h} \cdot \frac{1kW}{0.33kW(e)} = 5.15 \cdot 10^{-3} \frac{\$}{kWh(e)}$$

The fuel cycle cost is therefore 0.515 ¢/kWh(e).

MOX cycle — The MOX cycle can be represented as follows (for 1 kgIHM of fuel):



Assumptions

- Pu content of spent UOX 1.33%
- Pu content of fresh MOX: 7%
- Losses are neglected
- Burnup: 50 MWD/kgIGM
- Capacity factor: 0.9
- Thermal efficiency: 0.33

We now calculate the fuel cycle cost (per kgIHM fresh MOX fuel):

Table A-5.D.2 Single Recycle MOX Fuel Cycle Cost

	M_i (kgIHM)	C_i ($/kgIHM)	ΔT_i(yr)	DIRECT COST $M_i \cdot C_i$ ($)	CARRYING CHARGE $M_i \cdot C_i \cdot \phi \cdot \Delta T_i$ ($)
Credit for UOX SF	5.26	–400	4.25	–2105	–895
Reprocessing	5.26	1000	4.25	5263	2237
HLW storage and disposal	5.26	300	3.25	1579	513
MOX Fabrication	1	1500	3.25	1500	488
MOX Storage and disposal	1	400	–2.25	400	–90
			Total	6637	2253
			Grand Total	8890	

Assumptions

- Fuel irradiation time : 4.5 years
- Lead times:
  - 2 years for acceptance of spent UOX fuel,
  - 2 years for reprocessing,
  - 1 year for storage of HLW from reprocessing;
  - 1 year for MOX fuel fabrication
- The cost of acquiring depleted uranium is neglected

- Both the cost of separated uranium storage and the potential value of separated uranium material are not included in the analysis. Under current conditions, separated uranium is not used for fuel fabrication because using natural uranium is less expensive. Separated uranium is simply stored for possible use in the future. Since cost of storing separated uranium is very modest due to its low radioactivity, we ignore it in this analysis.
- The cost of HLW storage and disposal is assumed to be 25% lower than the cost of spent fuel storage and disposal. The HLW contains most of the fission products (including Sr-90 and Cs-137) and all the minor actinides present in the processed spent fuel, hence storage and disposal requirements are not expected to be much improved compared to spent fuel. However, because HLW has a lower volume and very small plutonium content, modest savings can be expected.
- The cost of storage and disposal for spent MOX fuel is assumed to be the same as for spent UOX fuel. Indeed, spent MOX is not reprocessed due to the degraded isotopic composition of its plutonium. We therefore consider it to be a liability comparable to spent UOX fuel.
- $\phi = 0.1$ per year

The fuel cycle cost is therefore $8,890/kgHM, or 2.24 ¢/kWh(e). This is approximately 4.5 times higher than for the once-through UOX cycle under U.S. conditions.

The incremental MOX fuel cost compared to UOX fuel cost will contribute to an increase in the cost of electricity in proportion to the ratio of MOX to UOX fuel in the entire fleet. Accordingly the incremental electricity cost for the fleet will be:

$$0.515 \text{ cents/kWe-hr } (1260/1500) + 2.24 \text{ cents/kWe-hr}(240/1500) = 0.791 \text{ cents/kWe-hr}$$

or a blended increase in the cost of electricity of 0.28 cents/kWe-hr in the MOX/UOX cycle compared to the once through UOX cycle.[31]

CONDITIONS FOR COMPETITIVENESS OF THE MOX OPTION

It is important to determine under what conditions the MOX fuel cycle becomes cost competitive with the once through UOX cycle. Cost components to consider are: (1) cost of natural uranium, (2) cost of reprocessing, (3) cost of MOX fabrication, and (4) cost of waste storage and disposal. Table A-5.D.3 presents the value that would make the fuel cycle cost of both options equal (breakeven value) for each of these four cost parameters.

Table A-5.D.3 Breakeven Values

COST COMPONENT	ORIGINAL VALUE	REQUIRED VALUE	REQUIRED/ORIGINAL
Natural uranium	$30/kgU	$560/kgU	19
Reprocessing	$1,000/kgIHM	$90/kgIHM	0.09
MOX fabrication	$1,500/kgIHM	Impossible	N/A
Waste storage and disposal	$400/kgIHM (SF)	$1,130/kgIHM	2.8
	$300/kgIHM (HLW)	$100/kgIHM	0.33

The cost of natural uranium is not likely to reach such high levels in the foreseeable future. The cost of reprocessing will probably never drop down to the required value of \$90/kgHM. As for waste storage and disposal, it is not reasonable to expect that the cost will be 11 times higher for UOX and MOX spent fuel than for HLW from reprocessing; indeed, although the volume of the HLW is much smaller, it still contains most of the fission products and all the minor actinides from the spent fuel. Therefore, its heat load in the first few hundred years should be comparable to that of spent fuel. It can also be observed from Table A-5.D.2 that, even if we assume that HLW storage and disposal can be done at zero cost, the total cost of the MOX option is still \$6798/kgIHM (obtained by subtracting the cost of HLW disposal, \$1579+\$513, from the total cost, \$8890). This is equivalent to 1.72 ¢/kWh(e), or more than 3 times the cost of the once-through option. It should be noted, however, that the original values selected for the costs of waste storage and disposal are not an absolute reference: important differences exist between countries because this cost depends on how difficult the nuclear waste problem is perceived to be. For some countries, the cost of waste disposal may very well be much higher than the reference values used here.

Finally, we consider the effect of changing our cost assumptions for ore purchase, reprocessing, MOX fabrication, and waste storage and disposal simultaneously. We find that the fuel cycle cost of the two options is equal under the following revised assumptions:

Table A-5.D.4 Breakeven Values (components adjusted simultaneously)

COST COMPONENT	UNIT	ORIGINAL VALUE	REQUIRED VALUE
Ore purchase	\$/kg	30	50
Reprocessing	\$/kgIHM	1,000	600
MOX fabrication	\$/kgIHM	1,500	1,100
Storage and disposal:			
Spent Fuel	\$/kgIHM	400	600
HLW	\$/kgIHM	300	100
Fuel cycle cost (both options)		6.3 mills/kWh	

Table A-5.D.4 shows that, by revising several cost assumptions in favor of plutonium recycling, we obtain equal fuel cycle costs for both options. Although the required ore purchase price is high and costs for reprocessing, MOX fabrication, and HLW disposal can be characterized as optimistic, they fall within the range of uncertainty defined by other fuel cycle cost studies (see Table A-5.D.6).

COMPARISON WITH OTHER ESTIMATES

There have been a number of studies on the economics of reprocessing with significant differences in assumptions. The most comprehensive study has been carried out by the OECD/NEA.[32] This study thoroughly evaluated the cost of the once-through and plutonium recycling fuel cycles, and concluded that the cost of the once-through option is about 15% lower (based on the assumptions presented in Table A-5.D.5). Thus, the findings of the OECD differ significantly from the result presented earlier, where the cost of the once-through option was found to be about 4 times lower.

There are several differences between the methodology used in the OECD study and the simple fuel cycle cost model used in this appendix. The OECD model is more detailed and the methodology for dealing with carrying charges is more involved. In addition, it sometimes uses different assumptions about the workings of the fuel cycles. For example, a credit is given for the irradiated uranium recovered in reprocessing, implying that it is used for fuel fabrication. In spite of such differences, assumptions regarding unit costs remain the dominant factor influencing fuel cycle cost estimates. The OECD study uses costs that are much more favorable to the reprocessing option. In fact, using the OECD assumptions in our model results in nearly equal costs for both fuel cycles. This is shown in Table A-5.D.5.

Table A-5.D.5 Fuel Cycle Cost Using OECD Estimates

COST COMPONENT	OECD ESTIMATE
Ore Purchase	50 $/kgHM
Conversion	8 $/kgHM
Enrichment	110 $/kg SWU
UOX fabrication	275 $/kgHM
SF storage and disposal	570 $/kgHM
Reprocessing	620 $/kgHM
HLW storage and disposal	60 $/kgHM
MOX fabrication	1,100 $/kgHM
FUEL CYCLE COST	
Once-through:	6.43 mills/kWh
MOX option:	6.80 mills/kWh

Table A-5.D.5 shows that OECD unit costs for the various back-end operations diverge significantly from the ones that were assumed in Tables A-5.D.1 and A-5.D.2. Such differences can be expected, as fuel cycle cost studies generally show very large uncertainties on such estimates. Indeed, few data on the cost of reprocessing and recycling operations are publicly available, and spent fuel or HLW disposal has not been implemented anywhere in the world, so the costs associated with these operations cannot be determined precisely. Furthermore, estimates are difficult to make for several reasons. First, engineering cost estimates for this type of activity are notoriously uncertain. Second, since fuel cycle facilities are high capital cost plants, the cost of capital assumption is very important.[33] Third, the cost estimates per unit product depend on assumption about both plant productivity and on allocation of fixed construction and development costs to unit output. Finally, the ultimate disposal cost for either spent fuel or HLW is not established. Certainly little confidence can be placed in any estimate on the *difference* in disposal costs for HLW and spent fuel.

Several other studies provide estimates of the unit costs for various fuel cycle operations. The OECD/NEA provides revised estimates in a recent study on advanced fuel cycles.[34] The Gen-IV Fuel Cycle Crosscut Group offers a range of estimates in its report.[35] Fetter, Bunn, and Holdren have offered an analysis of the economics of reprocessing versus direct disposal of spent nuclear fuel.[36] Finally, the National Research Council's study on Nuclear Waste[37] has an appendix on recycling economics. Note that the unit costs presented in these studies implicitly carry three charges: the direct cost of the activity, a capital charge that depends upon the assumed rate of return, and a capital charge for the "work in progress," i.e. the hold-up time for material flow through the system (for example, if it takes two years or three years of plutonium inventory to maintain a given material flow at a reprocessing plant, this influences the cost of reprocessing). We include in Table A-5.D.6 our "best guess" for the value of the parameters but stress, in the strongest possible terms, as can be seen from the difference in estimates made by other studies, the tremendous uncertainty in these numbers.

Table A-5.D.6 Comparison of Cost for Once-through and Recycle Process Steps

		ESTIMATED COST (lower bound - nominal - upper bound)			
COST COMPONENT	UNIT	OECD/NEA[34] (2002)	DOEGEN-IV[35]	Fetter, Bunn, Holdren[36]	Our Best Guess
Ore Purchase	$/kg	20-30-40	20-30-80	33	30
Conversion	$/kg	3-5-7	3-5-8	4-6-8	8
Enrichment	$/kg SWU	50-80-110	50-80-120	50-100-150	100
UOX fabrication	$/kgIHM	200-250-300	200-250-350	150-250-350	275
SF storage and disposal	$/kgIHM	410-530-650	210-410-640	0-150-300 (more than HLW)	400
UOX reprocessing	$/kgIHM	700-800-900	500-800-1,100	500-1000-1600	1,000
MOX reprocessing	$/kgIHM	700-800-900	500-800-1,100	—	—
HLW storage and disposal	$/kgIHM	63-72-81	80-200-310	0-150-300 (less than SF)	300
MOX fabrication	$/kgIHM	900-1,100-1,300	600-1,100-1,750	700-1,500-2,300	1,500

CONCLUSION

The simple fuel cycle cost model shows that the MOX option is roughly 4 times more expensive than once-through UOX, using estimated costs under U.S. conditions. Thermal recycle can be shown to be competitive with the once-through option only if the price of uranium is high and if optimistic assumptions are made regarding the cost of reprocessing, MOX fabrication, and HLW disposal.

The case is often advanced that disposing of reprocessed high level waste will be less expensive than disposing of spent fuel directly. But there can be little confidence today in any estimate of such cost savings, especially if disposal of TRU waste associated with thermal recycle facilities and operations is taken into account. Furthermore, our cost model shows that even if the cost of disposing of reprocessed high-level waste were zero, the basic conclusion that reprocessing is uneconomic would not change.

It should be noted that the cost increment associated with reprocessing and thermal recycle is small relative to the total cost of nuclear electricity generation. In addition, the uncertainty in any estimate of fuel cycle costs is extremely large.

Appendix 5.E — Price and Availability of Uranium

URANIUM RESOURCES AND RESERVES

The most authoritative source for estimates of uranium resources is the OECD/IAEA Red Book.[38] Figures from the latest edition are shown in Table 1.

Table A-5.E.1 OECD Conventional Uranium Resources (million metric tons, as of January 2001)

KNOWN CONVENTIONAL RESOURCES COST RANGES			REPORTED UNDISCOVERED CONVENTIONAL RESOURCES COST RANGES	
<40$/kgU	40 – 80$/kgU	80 – 130$/kg	<130$/kgU	Cost Range Unassigned
2.1	1.0	0.8	6.8	5.5
Total Uranium Resources: 16.2				

The term "reserves" refers to the known conventional resources that can be extracted using current technology under current economic conditions at various recovery costs. For example, from Table 1, reserves recoverable at costs = $40/kgU amount to about 2 million metric tons of uranium (MTU), enough for about 30 years at the current consumption rate.[39] However, reserves are only a small fraction of the total uranium resource base, which also includes known deposits that are not economic to recover at present prices or are surmised to exist with varying degrees of uncertainty in the vicinity of well-mapped deposits or by similarity of one unexplored geologic structure to other mapped and productive ones. When uranium prices rise, presently uneconomic resources will become economic to recover and mining companies will also have an incentive to delineate presently unmapped resources. As a result, new reserves will be created that can be used to fuel a growing installed nuclear capacity.

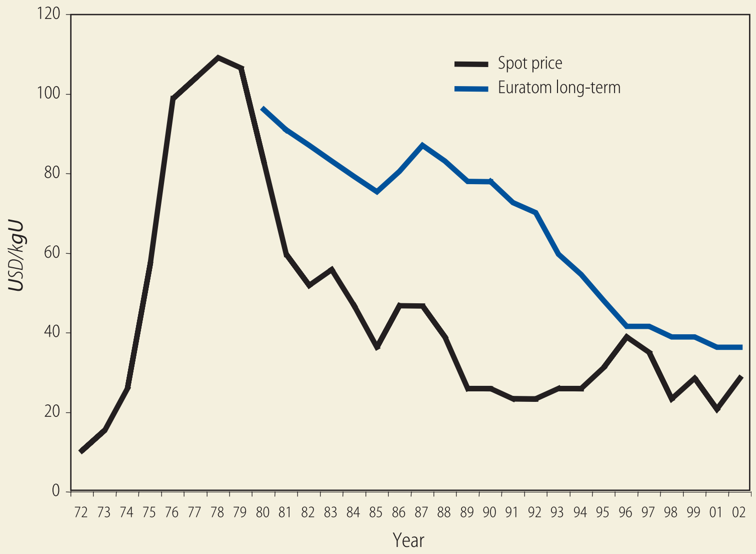
A quantitative example of the increased reserves that would be created as a result of higher prices has been given by the Uranium Information Centre in Australia: a doubling of the uranium price – which has been declining steadily since the late 1970s; see Figure 1 – from present contract levels could be expected to create about a tenfold increase in measured resources.[40] The term "measured resources" in this context refers to reserves extractable at costs = $80/kgU, which from Table 1 amount to about 3 million MTU. Thus, a doubling of uranium prices from about $30/kgU to $60/kgU could be expected to increase these reserves to approximately 30 million MTU. This can be compared with the requirements of the following 1500 GWe mid century scenario: installed nuclear capacity grows linearly from the current 350 GWe to 1500 GWe over 50 years and, after this growth period, no new plants are built and existing ones are operated for the rest of their lifetimes. The total production over the growth period is 41,625 GWe•y (assuming a capacity factor of 0.9), requiring 9.5 million MTU (assuming a uranium consumption of 226.5 MTU/GWe•y). Nuclear capacity then begins to decline: the newest plants still have 50 years of production ahead of them, but the units built at the beginning of the growth period must be decommissioned. Assuming an average remaining life of 25 years for the fleet, total electricity production over the decline period is 33,750 GWe•y, requiring 7.5 million MTU. The total uranium consumption for this scenario is therefore 17 million MTU. The 30 million MTU of reserves available if the uranium price doubled are more than sufficient to support this scenario.

INCREASED RESERVES FROM HIGH AND LOW GRADE ORES

The increase of reserves as a result of higher uranium prices could come from both high and low grade ores. The former are the "unconformity-related" deposits discovered starting in the late 1960s in Australia and Canada where typical ore concentrations exceed 10%. The world's largest, highest grade uranium mine at McArthur River in Saskatchewan, Canada is of this type. Estimates of reserves at McArthur River increased by more than 50% in 2001,[41] and further increases in reserves can be expected as a result of further exploration at this mine and other unconformity-related deposits. But such exploration followed by increased production is unlikely at today's uranium prices. Indeed, according to Bernard Michel, the former CEO of Cameco Corp., the McArthur River mine operator, uranium's current low price is "unsustainable".[42]

Most of the terrestrial uranium resource consists of large quantities of low grade ore. For example, phosphate deposits, which typically carry 10 to 300 parts per million of uranium, are believed to hold 22 million tons of uranium. A 1980 Scientific American article[43] suggests that the distribution of uranium resources as a function of ore grade is such that, in the region of current commercial interest, a reduction in ore grade by a factor of 10 increases the amount of available uranium by a factor of 300. Equivalently, for a decrease in ore grade by a factor of 2, uranium resources expand by a factor of 5.

Figure A-5.E.1 Uranium Prices, 1972–2001
annual basis



INCREASED URANIUM PRICES AND THE COMPETITIVENESS OF NUCLEAR ELECTRICITY

Table 2 shows that an increase in the price of uranium ore from 30$/kg to 60$/kg corresponds to an increase in ore price of about 1.10 mills/kWh. This corresponds to a modest increase of 2.2% in the cost of nuclear electricity.

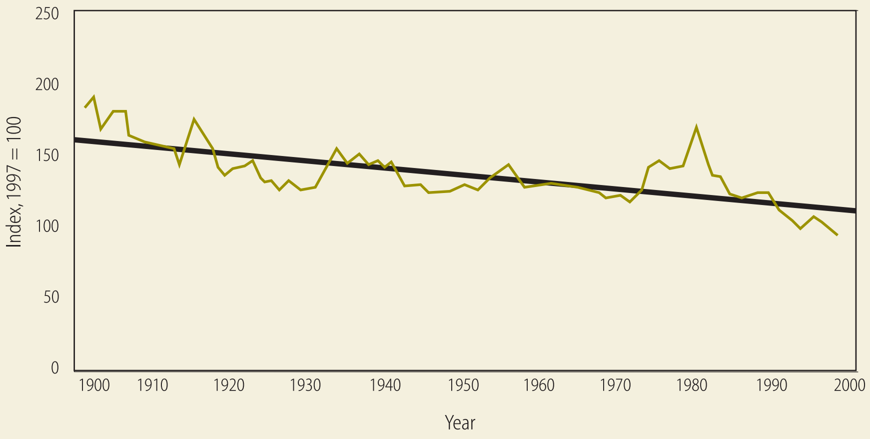
Table A-5.E.2 Cost of Uranium Ore as a Fraction of Cost of Electricity

	ORE PRICE (mills/kWh)			
ORE PRICE ($/kg)	Direct cost[a]	Carrying charge[b]	Total	% BUSBAR COST[c]
30	0.78	0.33	1.11	2.2%
50	1.29	0.55	1.84	3.7%
60	1.55	0.66	2.21	4.4%
100	2.59	1.10	3.68	7.4%
130	3.36	1.43	4.79	9.6%
200	5.17	2.20	7.37	14.7%

a. Assuming uranium consumption of 226.5 kg/MWey for LWRs.
b. Assuming a lead time of 4.25 years and a carrying charge factor of 0.1
c. Assuming busbar cost of 50 mills/kWh, or 5 ¢/kWh.

Furthermore, even if uranium prices increase as the most attractive deposits are depleted, there is good reason to expect that prices will not soar to prohibitively high levels. Historical data show that, over the past century, advances in exploration and extraction technologies have made it possible to recover lower grades and other less attractive resources at constant or even decreasing costs in constant dollars. The U.S. Geological Survey[44] provides data showing that the U.S. mine production composite price index has decreased throughout the 20th century, even as consumption of minerals increased significantly (see Figure 2). The USGS observes that advances in technology have been more than sufficient to overcome obstacles to supply. The USGS also provides striking data on the price and production levels of 4 selected commodities over the 20th century (see Table 3).

Figure A-5.E.2 Composite mineral price index for 12 selected minerals, 1900 to 1998, in constant 1997 dollars. Selected mineral commodities include 5 metals (copper, gold, iron ore, lead, and zinc) and seven industrial mineral commodities (cement, clay, crushed stone, lime, phosphate rock, salt, and sand and gravel).



Although uranium is different from other extractive resources because of its national security implications, we do not believe that this fact changes the fundamental process by which higher prices not only lead to exploration efforts but also create an incentive to innovate, which leads to technological progress and tends to hold prices down.

Table A-5.E.3 20th Century World Production and Price for 4 Selected Commodities

COMMODITY	PERIOD	INCREASE IN PRODUCTION (percent)	DECREASE IN CONSTANT DOLLAR PRICE (percent)
Aluminum	1900–1998	3,250	89.7
Copper	1900–1998	2,465	75.0
Potash	1919–1998	3,770	93.9
Sulfur	1907–1998	6,000	89.4

NOTES

1. By "real" we mean that all cash flows are expressed in constant dollars that have been adjusted for the effects of general inflation over the life of the project. However, the cash flows themselves must first be calculated using nominal dollars (including inflation) in order to properly calculate income tax obligations since tax depreciation is based on nominal construction costs and nominal interest payments are a tax deductible expense.
2. Taxable income may be reduced by allowing carry forward of net operating losses, most likely in early years of operation where both interest payments and tax depreciation allowances are substantial.
3. The model can be readily adapted to allow real prices for electricity to grow at a constant rate over time, but this complicates somewhat comparison of alternative technologies.
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7. Tarjanne, Risto and Rissanen, Sauli, *Nuclear Power: Least-Cost Option for Baseload Electricity in Finland,* The Uranium Institute 25th Annual Symposium, 2000.
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13. The TVA Act requires TVA to compensate state and local governments with tax equivalent payments.
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15. OECD, *Purchasing Power Parities and Real Expenditures: 1999 Benchmark Year,* 2002.
16. The currency exchange rate was 119 yen / U.S. dollar on May 28, 2003.
17. Construction costs for Yonggwang Units 5 and 6 were obtained through personal communication with Professor Soon Heung Chang of Korea Advanced Institute of Science and Technology (KAIST).
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26. Note that T_i can vary depending on the fuel management strategy

27. The unit used for mass of nuclear fuel the "kilogram of initial heavy metal", denoted kgIHM. We always refer to the initial mass of heavy metal in the fuel because the heavy metal atoms are fissioned as the fuel is irradiated, and therefore their mass decreases with time.

28. See, for example, Tsoulfanidis and Cochran, "The Nuclear Fuel Cycle", ANS, 1999, p. 62.

29. Alternatively, a simple linear relationship can be used to approximate the SWU requirement. For a tails assay of 0.3%, the following holds:

$$\frac{\text{kg SWU}}{\text{kg product}} = 2.07 \cdot x_p - 3.23$$

Using the same values as above for x_p, x_{nat}, and x_t, we get 6.09 kg SWU/kg product.

30. This value corresponds to the fee of 1 mill per kilowatt-hour of nuclear electricity generated paid to the DOE by each utility operating a nuclear power plant:

$$\frac{0.001\$}{kWh(e)} \bullet \frac{0.33kWh(e)}{1kWh} \bullet \frac{24h}{1d} \bullet \frac{1000kW}{1MW} \bullet \frac{50MWd}{1kg1HM} \approx 400 \frac{\$}{kgIHM}$$

31. We thank Matt Bunn for reminding us of the effect of increased MOX cost on blended electricity cost.

32. OECD/NEA "The Economics of the nuclear fuel cycle," 1994.

33. For example, the NRC study (footnote 7) estimates the levelized reprocessing cost for a 900 MTHM /year plant varies for different owner operators as follows: government $800/kgHM, utility $1300/kgHM, private venture $2000/kgHM.

34. OECD/NEA, "Accelerator-driven Systems and Fast Reactors in Advanced Nuclear Fuel Cycles", 2002

35. DOE, "Generation 4 Roadmap - Report of the Fuel Cycle Crosscut Group", 2001

36. Fetter, Bunn, Holdren, "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel", 1999

37. "Nuclear Waste – Technologies for separations and transmutation," Committee on Separation Technology and Transmutation systems, National Research Council, National Academy of Sciences, Appendix J, 1996

38 OECD/NEA & IAEA, "Uranium 2001: Resources, Production, and Demand", 2002

39. Current light water reactors consume approximately 226.5 MTU/GWe•y of electricity generated, hence the demand for today's fleet of 350 GWe is approximately 70,000 MTU per year, assuming a capacity factor of 90%.

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Appendix Chapter 7 — Waste Management

Appendix 7.A — International Programs in High Level Waste Management and Disposal

Most countries with nuclear power programs – and all the major ones — have adopted as their preferred technical approach to the final disposal of high-level waste the emplacement of sealed waste-bearing canisters in mined structures (‘geologic repositories’) hundreds of meters below the earth’s surface. No country has yet established an operating repository for high-level waste, and all have encountered difficulties with their programs. In many countries public and political opposition to proposed nuclear waste facilities and to the transportation of nuclear waste by road or rail has been intense, and public opinion polls reveal deep skepticism around the world about the technical feasibility of safely storing nuclear waste over the long periods for which it will remain hazardous. Many people think that no new nuclear power plants should be built until the waste issue has been resolved. In several major nuclear countries laws have been enacted whose practical effect will be to slow or even prevent the licensing of future nuclear power plants in the absence of demonstrable progress towards waste disposal. In other countries where decisions have been taken to phase nuclear power out completely, the nuclear waste problem has been prominently cited as a rationale.

Although geologic disposal is the announced technical strategy in almost every country, there are important differences in how countries are planning to implement it. Nowhere is repository development proceeding very quickly, but some countries are seeking to move forward as rapidly as domestic political and institutional constraints will allow, while others are pursuing a more leisurely approach. So far only two countries, the United States and Finland, have identified specific sites for their repositories

The U.S., Canada, and Finland are among a group of countries that are planning to dispose of their spent fuel directly. A second group of countries, which includes the U.K. and France, is reprocessing its spent fuel, and will dispose of the vitrified high-level waste from reprocessing operations. A third group is storing its spent fuel temporarily in central storage facilities, and has postponed the decision on whether or not to reprocess until a later date. A few countries — notably including Japan and Russia — have announced prohibitions on the direct disposal of spent fuel. There has been a long-running debate about the relative advantages of disposing of spent fuel directly versus reprocessed waste. We comment on this debate in the main body of this report.

National waste disposal programs also vary along several other important technical dimensions, including: (1) the candidate geologic media in which the repository will be located; (2) the geochemical environment; (3) the relative reliance on engineered versus natural barriers to radionuclide transport; (4) the thermal design of the facility – including the age of the waste at the time of emplacement.

A summary of international plans and programs in high-level waste disposal is contained in Table A-7.A.1.

Table A-7.A.1 High-level Waste Disposal Plans of Leading Nuclear Countries

COUNTRY	MANAGEMENT RESPONSIBILITY	PREFERRED/ SELECTED GEOLOGIC MEDIUM	EARLIEST ANTICIPATED REPOSITORY OPENING DATE	STATUS
United States	DOE	Volcanic tuff	2010	Site selected (Yucca Mountain, NV); application for construction license
Finland	Power companies (Posiva Oy)	Crystalline bedrock	2020	Site selected (Olkiluoto, SW Finland) — decision ratified by Parliament in May 2001
Sweden	Power companies (SKB)	Crystalline rock	2020	Searching for a suitable site
Switzerland	Power company coop (Nagra)	Crystalline rock or clay	2020 or later	Searching for a suitable site
France	Ind. Pub. Auth. (ANDRA)	Granite or clay	2020 or later	Developing repository concept
Canada	Crown Corp. (AECL)	Granite	2025 or later	Reviewing repository concept
Japan	National agency (NUMO)	Not selected	2030	Searching for suitable site
United Kingdom	Under review	Not selected	After 2040	Delaying decision until 2040
Germany	Federal contractor company (DBE)	Salt	No date specified	Moratorium on repository development for 3–10 years

Appendix 7.B — The Feasibility of Geologic Disposal

The concept of deep geologic disposal of high level wastes has been studied extensively in many national and international research programs for several decades. Considerable technical progress has been made over this period. Although practical experience in building and operating geologic repositories for high-level waste is still mainly limited to a few pilot-scale facilities, there is today a high level of confidence within the scientific and technical community that the geologic repository approach is capable of safely isolating the waste from the biosphere for as long as it poses significant risks. This view has been stated and supported in several recent national and international assessments [1-4]. It is based on: (1) an understanding of the processes and events that could transport radionuclides from the repository to the biosphere; (2) mathematical models that enable the long-term environmental impact of repositories to be quantified; and (3) natural analog studies which support the models and their extrapolation to the very long time-scales required for waste isolation. Natural analogs also provide evidence that key processes important to modeling the performance of geologic systems over long time periods have not been overlooked [5].

A geologic repository must provide protection against every plausible scenario in which radionuclides might reach the biosphere and expose the human population to dangerous doses of radiation. Various possibilities must be considered, including the risk of volcanic activity and the possibility of human intrusion into the repository, either inadvertent or intentional. Of the possible pathways to the biosphere, the one receiving most attention involves the entry of groundwater into the repository, the corrosion of the waste containers, the leaching of radionuclides into the groundwater, and the migration of the contaminated groundwater towards locations where it might be used as drinking water or for agricultural purposes.

Although the details vary among national programs, the basic approach to repository design in every case is based on a multibarrier containment strategy, combining a suitable geologic, hydrologic, and geochemical environment with an engineered barrier system that takes advantage of the main features of that environment. A well-chosen geologic environment will support and enhance the functioning of the engineered barrier system, while protecting it from large perturbations such as tectonic activity or fluctuations in groundwater chemistry due to glaciation or other climate changes [1].

The design proposed for the Finnish repository in the granitic rock at Olkiluoto highlights this systems approach [6]. The Finnish design, which is based on the earlier KBS-3 concept developed for the Swedish nuclear waste program, calls for the direct disposal of spent nuclear fuel assemblies in copper-iron canisters, surrounded by highly compacted bentonite clay, in vertical emplacement holes in crystalline bedrock at a depth of about 500 meters (see Figures A7.B.1 and A-7.B.2). The canister consists of a massive 1-meter diameter cast iron insert, surrounded by a 5-cm thick copper mantle (see Figure A-7.B.3.) The copper overpack serves as the primary containment barrier. The waste inventory in each canister is chosen such that the temperature at the canister surface will not exceed 100C. (The peak temperature occurs 10 to 20 years after repository closure.) In the chemically reducing environment characteristic of the Olkiluoto host rock, the copper is expected to corrode extremely slowly, delaying the release of radionuclides from the canisters for hundreds of thousands of years.[1] The compacted bentonite backfill provides a low permeability, strongly sorbing buffer layer, further delaying the release of most radionuclides into the surrounding rock. The bentonite pore size is small enough to effectively block the transport of any colloids which may form. The mineral content of the bentonite backfill is tailored to help accelerate the restoration of chemically reducing conditions in the vicinity of the canister following emplacement.[2] The cast iron canister insert will help to maintain a chemically reducing environment inside the canister even if ground water penetrates the copper overpack.[3] The primary function of the granitic host rock in this design is to provide a chemically and physically stable environment, thus enhancing the ability of the copper and bentonite engineered barriers to perform as expected.

Figure A-7.B.1 KBS-3 Repository Concept

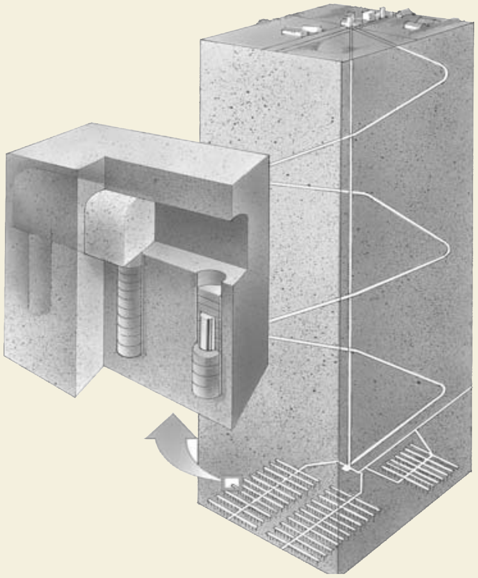
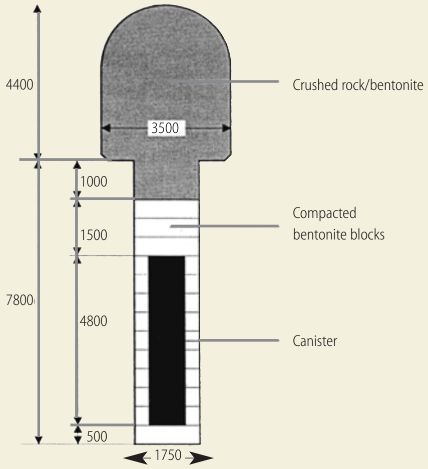


Figure A-7.B.2 Deposition Hole for Okliluoto Waste Canister

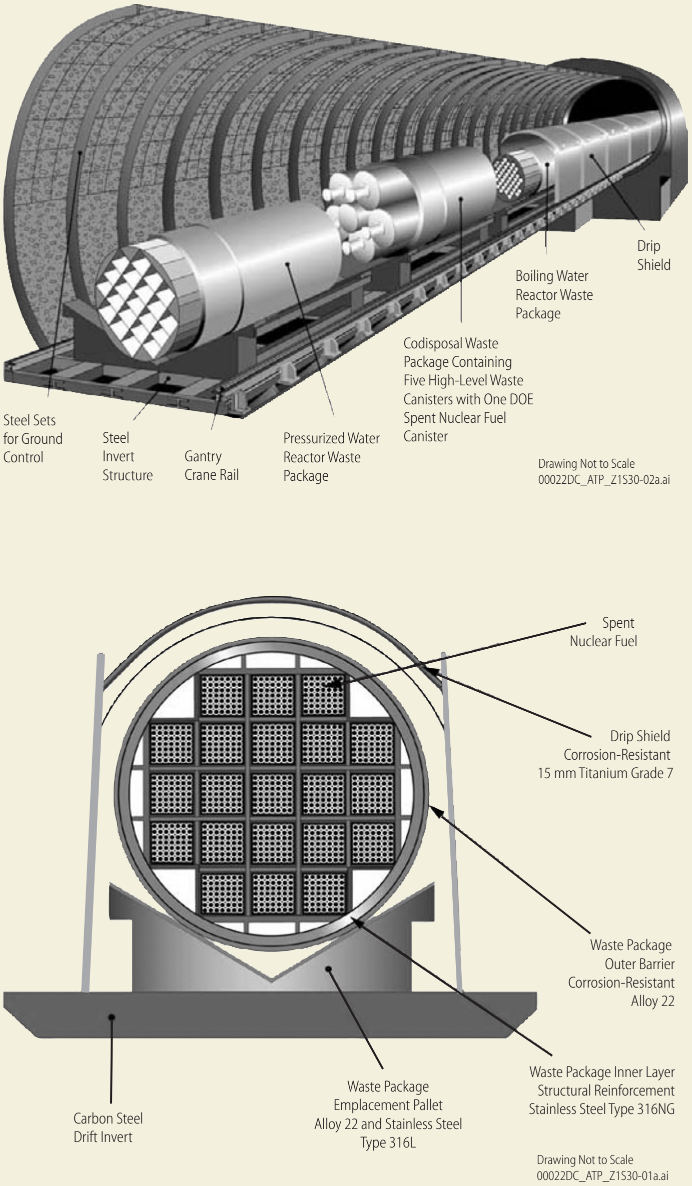


(from TILA-99, dimensions in mm)

Figure A-7.B.3 Prototype Canister

(Holds 12 assemblies from the Olkiluoto BWR power plant)

Figure A-7.B.4 Views of the Engineered Barriers at Yucca Mountain



processes which would lead to the release of radionuclides from the near-field to the far-field environment (copper corrosion, dissolution of the waste form, radionuclide transport through clay) are all well understood under expected repository conditions and this understanding is supported by natural analog studies [8,9]. This in turn has enabled the development of credible models describing the performance of the engineered barrier system.

The proposed U.S. repository at Yucca Mountain in Nevada, uniquely among current repository concepts, is located above the water table in the unsaturated zone – that is, the pores and fractures in the rock are only partially filled with water.[11] The presence of air trapped in rock pores and fractures and the flux of air through fracture systems will maintain an oxidizing environment surrounding the waste packages. The main repository design at Yucca Mountain has evolved in recent years to place more reliance on engineered barriers for overall radionuclide containment. In the present design (see Figure A-7.B.4) these consist of the waste packages themselves, cylindrical stainless steel canisters 5 meters in length, each containing 20-40 spent fuel assemblies, surrounded by a 2-centimeter thick shell of corrosion-resistant Alloy 22 (a nickel- based alloy), and protected by a 'drip shield' — a 1.5 centimeter thick canopy made of corrosion- resistant titanium that is designed to divert water infiltrating the repository from coming into contact with the waste canisters.

In one variant of the design, water will be kept away from the packages by ensuring that the temperature at the surface of the packages will exceed 100C, at least for the first 1000 years. Other engineered barrier systems have been proposed which would take advantage of the unsaturated conditions by creating zones favoring the flow of groundwater around the waste [12,13], or which attempt to control the water chemistry in the vicinity of the wastes[15].

If current plans come to fruition, the repositories at Yucca Mountain and Olkiluoto will have been in service for some time by mid-century. The experience with the earliest full-scale repositories can be expected to have a significant influence on future public attitudes toward the feasibility of high-level waste disposal. Whether these facilities experience trouble-free commissioning and operation or, less desirably, a series of unplanned-for developments will have an important bearing not only on the facilities themselves but also on public attitudes towards future siting efforts elsewhere.

Appendix 7.C — Radioactivity, Decay Heat, and Radiotoxicity Decay Profiles of Spent Fuel

Figures 7.1–7.3 in the main text respectively describe the radioactivity, decay heat, and radiotoxicity decay profiles of spent PWR fuel with a burnup of 50 MWD/kg HM. They were constructed from data generated by Zhiwen Xu in the course of his Ph.D. research at MIT [17].

The radiotoxicity is a proxy for the risk posed by the spent fuel in a geologic repository. It is defined as the total volume of water required to dilute all of the radionuclides contained in 1 MT of spent fuel down to their maximum permissible concentrations, where the maximum permissible concentration is in turn determined such that an individual could safely obtain his total water intake from such a source. Thus,

$$\text{radiotoxicity at time t} = \sum_{i}^{\textit{all radionuclides}} \left(\frac{\lambda_i N_i(t)}{MPC_i^{water}} \right)$$

where $\lambda_I N_i(t)$ is the quantity of radioisotope i present in 1 MT of waste at time t (in Bq/MT), and MPC_i is the maximum permissible concentration of isotope i in water (in Bq/m^3.)

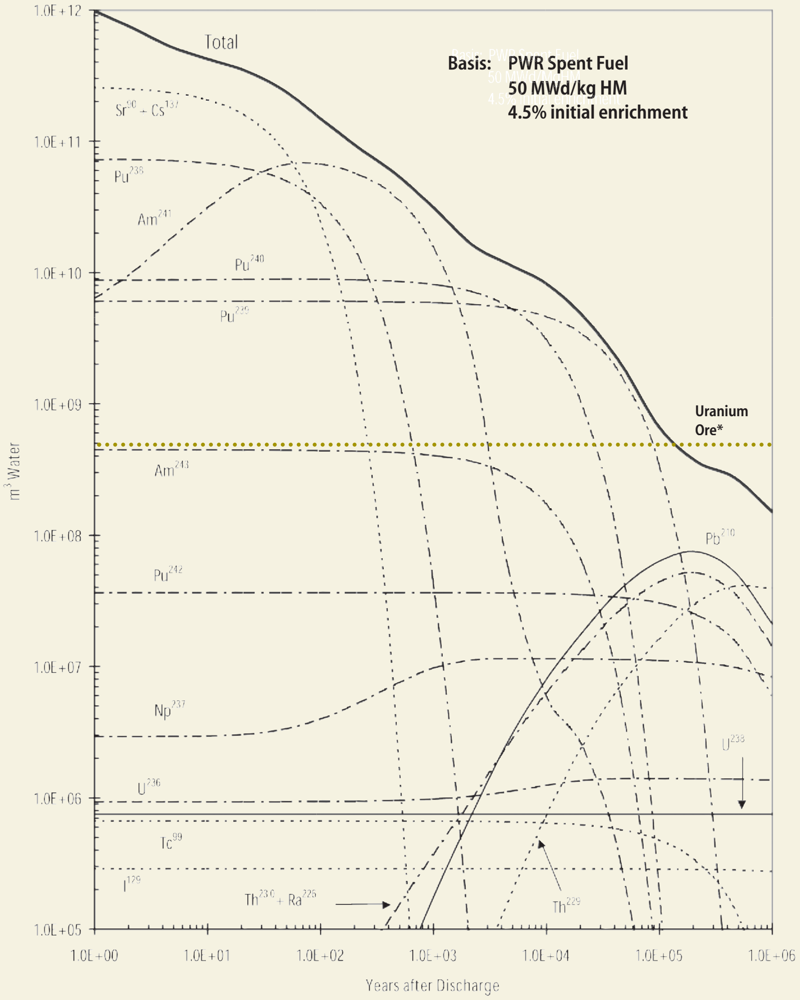
The calculation of the maximum permissible concentration for each radionuclide was based on the assumption that an adult would ingest water containing the radionuclide at a constant rate of 2 liters per day over the course of a year. The concentration limit was determined by imposing the requirement that the individual should receive a committed effective dose of no greater than 50 millirems from this source. The limits were computed using the radionuclide ingestion dose coefficients for adults published by the International Commission on Radiological Protection [18].

To illustrate for the case of strontium-90: The ICRP-72 ingestion dose coefficient for ^{90}Sr = 2.8 x 10^{-8} Sv/Bq. Thus, the total allowable annual intake for a committed effective dose of 5 x 10^{-4} Sv (or 50 mrem) = 5 x 10^{-4} /(2.8 x 10-8) = 1.786 x 10^{4} Bq/yr. The maximum allowable concentration of ^{90}Sr is then just

$$\frac{1.786 \times 10^4 \ \ (Bq/year)}{0.002 \ (\mathrm{m}^3/\mathrm{day}) \times 365 \ (\mathrm{days/year})} = 2.45 \times 10^4 \ Bq/m^3$$

The radiotoxicity decay profile for spent fuel is shown in Figure A-7.C.1. Also shown for comparison is the radiotoxicity of an 'equivalent' amount of natural uranium ore — that is, the quantity of uranium ore that would have to be mined in order to generate the metric ton of spent fuel. According to the figure, after about 150,000 years the spent fuel will be no more hazardous than the parent ore, implying that a high-level waste repository should be designed to isolate the spent fuel for approximately that length of time. Of course, such comparisons take no account of the different environmental risk factors for

Figure A-7.C.1 Radiotoxicity Decay Profile for Spent PWR Fuel (m³ water/MT fuel)



The radiotoxicity index corresponds to an ingested dose of 50 mrem/year and was calculated using ICRP-72 adult dose coefficients (1996)

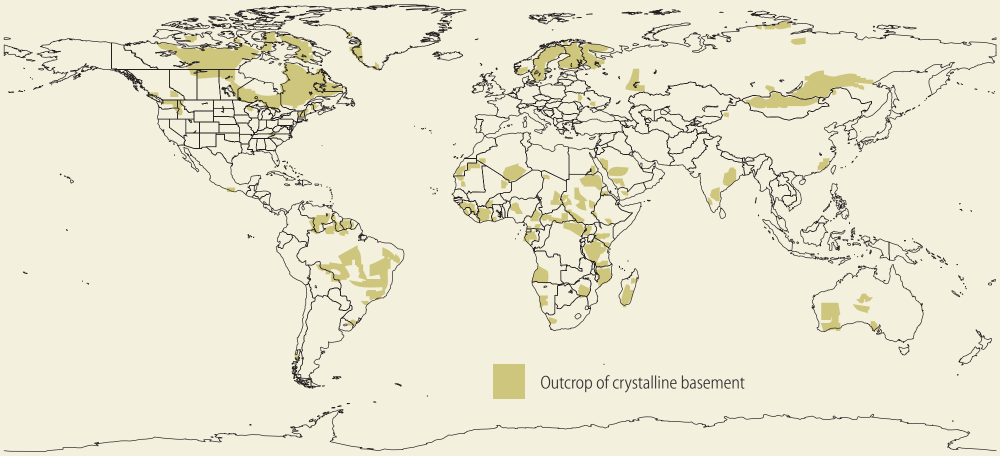
* Amount of ore mined to produce 1 MT fuel @ 4.5% U-235 enrichment

these materials. Uranium ores (and other naturally occurring hazardous materials) are deposited randomly, frequently in permeable strata, and with groundwater often present in abundance. By contrast, high-level waste will be buried at depths of several hundred meters in locations selected for geological stability, low groundwater flows, and remoteness from population centers. On the other hand, a high-level waste repository is a man- made structure, with shafts and boreholes linking it to the biosphere. Moreover, as noted previously the presence of heat-generating materials has the potential to disrupt the geohydrological environment and accelerate the corrosion of the waste canisters. All of these factors — and others besides — must be considered in assessing the actual risk posed by a waste repository. In short, although frequently used as an indicator of the radiological risk posed by the waste, the radiotoxicity index is an imperfect proxy of limited utility.

Appendix 7.D — Deep Borehole Disposal

An alternative to the construction of mined geologic repositories is to place waste canisters in deep boreholes drilled into stable crystalline rock several kilometers below the earth's surface. [1,19-24] At these depths, vast areas of crystalline basement rock are known to be extremely stable, having experienced no tectonic, volcanic, or seismic activity for billions of years. At such depths, moreover, the chemical environment is strongly reducing, and if any groundwater is present at all it is likely to be highly saline. Preferred locations for waste boreholes are in tectonically stable cratons and plutons in regions where there has been no major faulting and which are relatively easily accessible from the surface (i.e., the overburden of sedimentary rock should ideally be less than 1 kilometer thick.)

Figure A-7.D.1 Distribution of Crystalline Basement Rock Exposed to the Surface



Prepared by Grant Heiken, Los Alamos Scientific Laboratory, Earth and Environmental Sciences Division

A detailed Swedish study of the deep borehole concept conducted about 15 years ago proposed a hole 80 centimeters in diameter at depth, into which would be placed canisters of length 4.4 meters and diameter 50 centimeters, with each canister separated from its neighbors by plugs of compressed bentonite clay. [19] If each canister contained the rods from two PWR fuel assemblies, a single borehole 4 kilometers deep, with the lower 2 kilometers filled with waste canisters, could store 10-15 years of spent fuel discharged by a 1000 MWe PWR. In other words, such a reactor might require 3-4 such holes to store the spent fuel discharged over its lifetime. The Swedes calculated that about 35 boreholes would be required to accommodate the forecast quantity of waste from Sweden's 11 nuclear power plants.

The deep borehole concept was one of several high-level waste disposal schemes under consideration before the mined repository approach emerged as the preferred strategy in the U.S. and elsewhere in the 1980s.[4] Since then it has attracted little attention and few development resources, but in the meantime there have been significant advances in relevant technologies. Drilling to depths of a few kilometers, still quite rare in the 1970s and 1980s, is now fairly routine in the oil and gas industry, and major advances in well logging techniques permit more accurate characterizations of geophysical and geochemical parameters at depth.

An initial screening suggests that large areas of the world may have geology appropriate for deep waste boreholes.[5] Figure A-7.D.1 shows the global distribution of crystalline basement rock that is exposed at the surface. In practice, crystalline rock that is located within 2 km of the surface provides adequate access for deep drilling.

that is exposed at the surface. In practice, crystalline rock that is located within 2 km of the surface provides adequate access for deep drilling.

Suitable host rock also occurs beneath the sea floor. For this reason the concept may be particularly interesting for densely populated countries like Japan, Korea, and Taiwan. Since most of the power reactors in these countries (and indeed in most countries) are located on or close to the coast, the possibility arises of constructing artificial offshore islands from which to drill beneath the seabed. Such islands could also serve as temporary storage venues for the spent fuel, eliminating the requirement for on-land waste transportation and storage.

The pervasiveness of suitable geology for deep boreholes introduces the possibility of dispersed waste disposal sites, thus reducing the need for spent fuel transportation. Co-locating boreholes with at least some reactor sites may be technically feasible. Alternatively, the boreholes could be consolidated at a central location. For example, a borehole array occupying an area of 4 km^2, roughly equal to the subsurface footprint of the Yucca Mountain repository, could accommodate more than the Yucca Mountain spent fuel inventory.[6]

NOTES

* The radiotoxicity calculations presented in Appendix 7.C were carried out by Dr. Brett Mattingly, who also provided valuable research support in the preparation of this Appendix.

1. Several modeling studies of copper canister corrosion under expected repository conditions have been performed in Sweden, Finland, and Canada. Each of these studies has estimated an expected copper canister lifetime exceeding one million years. [7]. Natural analog studies also indicate that elemental copper corrodes at extremely slow and predictable rates in such conditions. [8]
2. Free oxygen is introduced into the near-field environment during waste emplacement operations. Oxidation of pyrite in the bentonite backfill helps to restore a reducing environment around the canister within a few hundred years at most. During this oxic phase, the copper mantle is not expected to corrode by more than 2.5 mm. Copper corrosion under reducing conditions occurs via sulfide attack. Dissolved sulfide concentrations will be limited by equilibrium with sulfide impurities in the bentonite. The copper corrosion rate under reducing conditions is much slower than under oxidizing conditions[6,7].
3. A reducing environment strongly inhibits the dissolution and transport of actinides in groundwater. The solubility of the long-lived fission product isotope Tc-99 is also significantly decreased in reducing conditions[14,16].
4. Other options considered at that time were disposal in surface facilities, extra-terrestrial disposal, ice sheet disposal, and disposal in the sedimentary layer under the deep ocean floor. Of these, only the sub-seabed disposal option has attracted any subsequent attention
5. Grant Heiken, Los Alamos Scientific Laboratory, Earth and Environmental Sciences Division, personal communication, November 15, 2002.
6. For example, suppose the borehole drillsites were arrayed on a grid measuring 2 km x 2 km with a spacing of 0.5 km. Suppose in addition that ten holes, each 5 km deep, were drilled from each drillsite, with the lower 3 km of each hole filled with waste canisters. If each canister is 5 meters in length and contains 1 PWR assembly, or equivalently about 0.5MT of spent fuel, the total spent fuel inventory in the borehole repository would be about 75,000 MT – somewhat more than the legal limit at Yucca Mountain. The storage capacity of the repository could be further increased by increasing the number of boreholes per drillsite, increasing the active length of each borehole, and increasing the packing density of the spent fuel rods in each canister by reconstituting the assemblies. If each of these parameters was doubled, say, the total capacity of the borehole repository would be more than 8 times that of Yucca.

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Appendix Chapter 9 — Public Attitudes

EUROPEAN ATTITUDES TOWARD NUCLEAR POWER

Our projection under the global growth scenario is that the U.S. will have the largest expansion in its nuclear fleet, followed by Europe and Japan. Some European countries have committed to eliminating or lessening their reliance on nuclear power for political reasons.

Attitudes toward nuclear power vary greatly across European countries ("European and Energy Matters, 1997," EUROBAROMETER 46.0, Directorate General for Energy, European Commission, February 1997). The survey additionally reports the following interesting trends:

> "On the country level, Finland, The United Kingdom and Sweden report with the highest frequencies to think the development of nuclear power stations is worthwhile. Compared to the figures of 1993, there are big downward shifts in Belgium and Italy in the proportions of respondents that say they think the development of nuclear power stations is worthwhile."
>
> The socio-demographic groups that to the highest extent think this is worthwhile are:
>
> - Those who finished their full time education at the age of 20 or after; and
> - Those with political preferences toward the right.
>
> Also, there is a noticeable difference of 8 points between the men and women that say the development of nuclear power stations is worthwhile, was recorded.
>
> The countries that to the highest extent state the development of nuclear power stations involves unacceptable risks are Austria, Greece, Denmark and Ireland.
>
> Big upward shifts in the percentages recorded, occurred in Denmark, West Germany, Greece, Spain, Ireland, Italy, Luxembourg and The United Kingdom. A noticeable downward shift was recorded in France.
>
> The socio-demographic groups that most often say it involves an unacceptable risk are those with left political preferences and those who are still studying.
>
> The French, the Dutch and the Swedes record the higher proportions of respondents stating that the development of nuclear power stations should be neither developed, nor abandoned."

Our analysis of U.S. survey data finds much weaker correlation of demographics with attitudes toward nuclear power than is evident in the Eurobarometer data. Indeed, once we control for perceptions of the technologies, the correlations vanish altogether. We suspect that the same is true in Europe: opinions are driven by economics, environmental harms, and solutions to the waste problem[1]. Replicating our survey in Europe and other countries is important for understanding the nature of public attitudes toward nuclear power and other energy options. For a discussion of the roots of French opinions toward nuclear power see: http://www.pbs.org/wgbh/pages/frontline/shows/reaction/readings/french.htmlattributes

MIT ENERGY SURVEY

Sample Statistics. Knowledge Networks drew a random sample of 1800 people from their panel to participate in an energy survey; 1358 completed the survey. Survey respondents were 18 years or over, with the median respondent about 45 years old. The typical person had income between $40,000 and $50,000. Thirty-one percent completed high school; 28 percent had some college; and 24 percent had a bachelor's degree or higher. Three-quarters of the respondents were white; 62 percent were married; 52 percent were female.

Question Wordings and Distribution of Responses On Future Use:

Question 11: To make more electricity to meet the country's needs over the next 25 years, new power plants will have to be built. Companies and government agencies need to start planning today. How should we meet this demand?

DISTRIBUTION OF RESPONSES (all groups):

FUEL	NOT USE	REDUCE A LOT	REDUCE SOMEWHAT	KEEP SAME	INCREASE SOMEWHAT	INCREASE A LOT
Coal	4.8%	23.3	29.9	25.0	10.7	6.0
Dams	1.4	3.8	11.2	31.1	34.2	18.0
Gas	1.3	6.3	24.1	37.2	22.7	8.1
Nuclear	9.2	19.2	18.6	24.6	18.3	9.8
Oil	3.4	19.7	33.6	30.2	9.5	3.2
Solar	1.4	2.3	4.9	13.6	27.0	50.4
Wind	1.6	2.5	4.7	13.9	24.4	52.6

Question 8. How expensive do you think it is to produce electricity from each of the following fuels?

1. Very Expensive;
2. Somewhat Expensive;
3. Moderately Priced;
4. Somewhat Cheap;
5 Very Cheap

DISTRIBUTION OF RESPONSES (all groups):

	EXPENSIVE		MODERATELY	INEXPENSIVE		
FUEL	**Very (1)**	**Somewhat (2)**	**Priced (3)**	**Somewhat (4)**	**Very (5)**	**AVERAGE**
Coal	13.4%	24.5%	35.1%	21.4%	5.6%	2.8
Nuclear	38.8	33.0	19.3	7.4	2.0	2.0
Natural Gas	11.8	32.8	42.5	11.5	1.3	2.6
Oil	25.2	42.1	26.7	5.3	0.7	2.1
Hydroelectric	9.9	24.5	34.7	22.4	8.9	3.0
Solar	9.9	19.4	22.7	28.1	19.9	3.3
Wind	4.5	11.6	19.3	31.1	33.5	3.8

Question 7. Some ways of generating electricity may be harmful to the environment we live in because they produce air pollution, water pollution, or toxic wastes. How harmful do you think each of these power sources is? (Higher values are less harmful)

DISTRIBUTION OF RESPONSES:

	VERY	**MODERATELY**	**SOMEWHAT**	**SLIGHTLY**	**NOT**	**AVERAGE**
Coal	32.9%	31.7%	24.2%	9.0%	2.3%	2.2
Nuclear	45.1	22.5	17.3	10.4	4.7	2.1
Natural Gas	6.9	18.0	35.0	29.4	10.8	3.2
Oil	23.4	37.1	28.0	8.6	2.8	2.3
Hydroelectric	6.0	12.0	19.0	29.2	33.8	3.7
Solar	2.7	3.1	8.9	14.0	71.2	4.5
Wind	1.7	2.9	6.9	12.8	75.8	4.6

Question 9. There are approximately 100 nuclear power plants in the United States. How likely do you think it is that in the next 10 years there will be a serious accident at a nuclear power plant?

Almost Certain	18.9%
Very Likely	23.0
Somewhat Likely	31.9
Not Very Likely	23.6
Not At All	2.3

Question 10. Do you agree or disagree with the following: Nuclear waste can be stored safely for many years.

Strongly Agree	5.9%
Agree	30.3
Disagree	39.7
Strongly Disagree	23.9

REGRESSION ANALYSIS EXPLAINING FUTURE USE

For each fuel, Question 11 is the dependent variable. For all fuels, responses to Questions 7 and 8 are used to measure perceived harms.

Table A-9.2 Relationship between Perceived Harm and Perceived Cost and Future Use, Holding Constant Other Factors

	IN FUTURE INCREASE/]REDUCE USE OF …						
	Coal	Hydro	Gas	Nuclear	Oil	Sun	Wind
Perceived (Lower) Harm:							
Coal	+.38**	–.03	–.09	–.06	+.07	–.13**	–.13**
Dams	–.09	+.32**	–.13**	–.04	–.05	–.02	+.01
Gas	+.03	–.13**	+.30**	–.08*	–.00	–.06	–.05
Nuclear	–.07	–.05	–.09**	+.35**	–.14**	–.02	–.00
Oil	_.06	–.16**	+.06	–.00	+.29**	–.13**	–.12**
Sun	–.10*	+.02	–.10*	–.01	–.22**	+.30**	+.12**
Wind	–.10*	–.01	–.03	–.11*	–.14**	+.10*	+.27**
Perceived (Lower) Cost:							
Coal	+.09**	–.04	–.01	+.06	+.01	–.04	–.06*
Dams	–.05	+.15**	–.10**	–.06	–.12**	+.07**	+.11**
Gas	–.07	+.02	+.15**	–.12**	+.00	.01	+.01
Nuclear	+.03	–.05	+.01	+.14**	–.01	–.06*	–.08**
Oil	–.05	+.04	–.01	–.00	+.06*	–.02	–.01
Sun	–.02	–.10**	+.02	+.01	–.03	+.10**	+.02
Wind	+.05	+.06	–.01	+.00	+.08*	–.12**	–.05
Nuke Accident	+.01	+.03	+.05**	–.22**	–.00	+.08**	+.05
Nuke Waste Safe	–.01	–.05*	+.00	+.18**	+.01	–.06**	–.08**
Global Warming	–.03	–.02	+.00	–.02	+.05	+.00	+.01
R-squared	.49	.53	.57	.55	.47	.49	.46

(% of y explained)
* Statistically significant at p<.05.
** Statistically significant at p <.01.

In summary, the results of our survey find

- The public correctly perceives the relative costs and benefits of nuclear power compared to other power sources.
- The public has yet to connect the way we generate power to carbon emissions and global warming.
- Additional information may not be enough to change public attitudes toward nuclear power.

NOTE

1. For a discussion of the roots of French opinions toward nuclear power see: http://www.pbs.org/wgbh/pages/frontline/shows/reaction/readings/french.htmlattributes